Selective Backbone Construction for Topology Control in Ad Hoc Networks

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***Abstract*— A key step in controlling topology in ad hoc networks is the construction of the backbone which is then used to transfer data. Nodes that are not part of the backbone can then go to sleep to save energy and increase the lifetime of the network. Centralized backbone construction algorithms give better performance but incur high communication overhead, while localized algorithms lack sufficient topology information needed to construct efficient backbones. In this paper we present Selective Backbone Construction (SBC) which starts by electing a small number of seed nodes in the backbone and then completes its construction by making a sweep of the network spreading outwards from the seed nodes. During the latter process, topology information is transferred to allow better coordinator selection decisions. We compared SBC with other power-saving protocols in a variety of tests featuring different mobility levels, traffic patterns, and node densities. Our experiments show that SBC is more efficient in saving energy and extending network life while providing satisfactory network performance when compared with 802.11, 802.11 PSM, and GAF.**

Keywords: Ad hoc networks, topology control, backbone, energy conservation.

I. INTRODUCTION

Multi-hop wireless ad hoc networks consisting of mobile hosts are receiving significant attention from both researchers and application developers. Hosts forming an ad hoc network take equal responsibility in maintaining networking functions. Every host provides routing service to other hosts and also depends on other hosts to deliver messages to remote destinations. Wireless ad hoc networks do not rely on existent infrastructure and centralized administration, so they have broad applications in volatile environments such as battlefield and diaster relief situations.

In ad hoc networks a channel is usually shared among many hosts. The sharing increases the complexity of route discovery, reduces the network performance, and increases energy consumption due to aggravated radio interference. Topology control is a technique used in ad hoc networks to address these problems. Topology control optimizes network topology and reduces routing cost by restricting the connections among pairs of hosts. If we view an ad hoc network as a graph $G = (V, E)$, where V is the host set and E is the set of links between hosts, the initial graph is heavily connected. Topology control removes unnecessary links from the initial graph and derives a connected sub-graph with fewer links which enables efficient routing. Another important application of topology control is to save energy in ad hoc networks. Energy consumption is a serious issue in ad hoc networks. Because mobile devices usually rely on power supplies of limited capacity, such as batteries, energy conservation is critical to the operational lifetime of ad hoc networks. Moreover a significant part of energy is consumed by networking cards as noted in [7].

Topology control for energy conservation purpose can be implemented in two ways. In one approach, hosts adjust the strength of transmission power to maintain a proper number of neighbors. The work in [16] [11] took the energy consumption into account and determined a proper transmission range that provides sufficient network connectivity and efficient usage of energy. The second approach of topology control exploits the node redundancy in ad hoc networks. Ad hoc networks have high level of node redundancy because of the large broadcast range of radios. One node can cover a large area and reach a number of neighboring nodes. Therefore a subset of nodes can be selected to serve as the coordinators through which all nodes can, directly or indirectly, communicate with each other. The coordinators form the backbone of the network. The nodes that are not in the backbone have at least one neighboring node that is in the backbone, i.e. all the nodes in the network are connected through the backbone. The non-backbone nodes that do not have active communication can safely go to sleep to save energy. The duration of sleep time depends on how long the backbone can be maintained – which is usually dozens of seconds.

By using a backbone more energy can be saved than by simply adjusting transmission range because energy dissipation happens not only during active communication such as transmitting and receiving packets, but also when nodes are in idle state. The study in [3] shows that the ratio of energy consumed by networking card in sending, receiving and idle states is 1.7:1.2:1. Thus, the energy consumed in idle state constitutes a significant part of total energy consumption and cannot be ignored.

It is desirable to form a small backbone to save more energy. The problem of constructing a minimum backbone is equivalent to finding the *Minimum Connected Dominating Set* of a graph. This problem has been proven to be NP-complete even when the complete network topology is available. In ad hoc networks, node movement and high cost of transfering

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information across the whole network make it impractical to use a centralized backbone algorithm. Thus, many distributed algorithms have been proposed. One such algorithm is based upon *clustering*. In this approach, nodes are first added to the dominating set according to a local condition. These nodes are called *clusterheads*. Clusterheads then choose their neighbors as *gateways* to connect with other clusterheads and the network. Different heuristics exist for electing clusterheads and gateways. Characteristics upon which these heuristics are based include node IDs, node degrees, mean received-signal strength variations, power levels, and the speed at which nodes are moving. In Bao et al. [1] a variety of such heuristics are compared. Recent works [1] [20] combine the consideration of several factors simultaneously.

In addition to the clusterng approach, other works form the backbone by non-deterministic negotiations, where nodes decide to join or quit backbone mostly based on their observation of the nearby topology change. In SPAN [3], a node joins the backbone if it has two neighbors that are not connected either directly or through a third node. The similar idea is also explored and proved correct in [18]. GAF [19] constructs the backbone based upon the geographic location of nodes. It divides space into grids of equal size and elects one coordinator in each grid. The size of grid is choosen in such a way that a node any where in one grid can reach another node any where in an adjoining grid.

In this paper we propose an innovative algorithm for constructing the backbone called *Selective Backbone Construction* (SBC). Our algorithm employs a different procedure to form backbone. The backbone construction in SBC starts from a small number of *seed nodes* and propagates outwards to sweep the network. When a node selects its neighbors to include in the backbone, it also transfers the topology information it knows so far to these neighbors. Thus, the neighbors can make more intelligent coordinator selection decisions based upon more topology information and avoid redundancy. When choosing coordinators, SBC simultaneously considers the energy requirement, movement and location of nodes to maximize energy conservation, and ability to maintain good networking performance. Our experiments show that SBC is more efficient in saving energy and extending network life while providing satisfactory network performance when compared with 802.11, 802.11 PSM, and GAF.

The rest of the paper is organized as follows. In section 2, we describe the design of SBC and present the SBC algorithm in detail. In section 3 we present the experimental results. We discuss some additional related work in section 4. Conclusions are given in section 5.

II. SELECTIVE BACKBONE CONSTRUCTION

In this section, we first describe our design consideration for SBC, and then present the SBC algorithm in detail.

A. Design Consideration

Our system assumes a bidirectional connection between two nodes. Several approximation algorithms for choosing coordinators under this assumption are studied and compared in [4] [8]. In general, centralized algorithms give better performance than decentralized algorithms because of better consideration based on global topology information. However, the cost of implementing centralized algorithms could be prohibitive in an ad hoc network, which features low bandwidth and unreliable channels. The continuous change of topology also makes it hard to maintain a consistent global view of a mobile ad hoc network. On the other hand, localized algorithms usually rely on insufficient topology information and construct less efficient backbone. SBC tries to address this problem using an incremental method. In SBC, first each node obtains the topology information in its two-hop neighborhood. Next, a small number of seed nodes are elected as coordinators. Seed nodes choose appropriate neighbor nodes as coordinators to connect to remote nodes. The newly selected coordinators repeat the selection process to expand the backbone further until the whole network is covered. At the beginning, SBC constructs backbone based on limited topology information. However, as the coordinator selection proceeds, more topology information about existent backbone is accumulated and transferred to selected nodes to help them make a better decision.

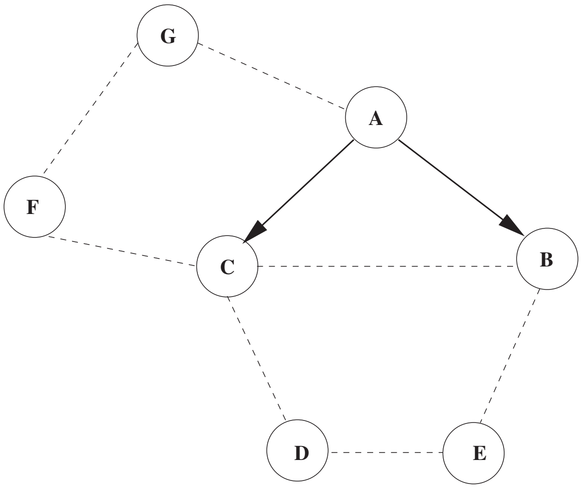


Fig. 1. Illustration of SBC.

The propagation process of SBC is illustrated in Figure 1. Lets consider the situation in which node A is chosen as coordinator at first and then it selects node B and C to connect to other nodes that it cannot reach directly. Next nodes B and C examine their neighbors. When C gets the selection notification from A, it knows that A and B are coordinatiors. Thus, C excludes those remote nodes that can be reached through A and B. Given this information C does not choose additional coordinators because its remote nodes are all reachable through A and B. In a similar fashion when B gets the selection notification it also knows that A and C are coordinators. Since all nodes remote to B can be reached through A and C, no additional coordinators are selected. The information of selected coordinators that is made available to B and C as well as the two-hop topology information prevents selection of additional nodes as coordinators. In particular, node C does not select node F to reach G and node B does not select node E to reach D. So the final backbone consists of three nodes, which is the optimal solution for this example.

The actual SBC is more complex than the example because we have to consider many factors such as the expected lifetime of the constructed backbone and average resource consumption across the nodes. To choose proper coordinators, nodes have to be prioritized. We consider two factors affecting the priority of nodes: available *energy* of nodes; and the *speed* at which nodes are moving. If a node with low energy or high speed is chosen into the backbone, its neighborhood will become void or change shortly due to the fact that either the node runs out of energy or it leaves that area. In both situations, backbone has to be reconstructed in that area, which is not desirable because nodes have to wake up after sleeping for a short time. Thus, a node with high energy and low speed should be given higher priority and have a better chance to become a coordinator. SBC formulates the priority of a node as $\frac{energy}{2^{\alpha * speed}}$. If a node does not move, its capability of being coordinator depends on its energy level, which decides how long it can serve the network; otherwise, the node's speed adversely affects its capability to act as an effective coordinator. The parameter α controls the degree by which the speed effects the priority. With larger α, we prefer nodes moving at low speeds to construct a more stable backbone. Simulation results presented later in the paper are obtained by setting the value of α to be 0.25.

So far most of the research work around backbone formation focuses on reducing the size of the backbone. Such effort could lead to more energy conservation, but also degrade the network performance because of congestion and resource competition. SBC considers the balance of energy conservation and network performance. SBC applies a couple of rules to construct an efficient backbone without significantly affecting the network performance, which are detailed in next section.

B. Selective Backbone Construction Algorithm

SBC constructs backbone in two steps. In the first step, one or more backbone seed nodes are elected. Next they choose their neighbor nodes into backbone to connect the whole network. When SBC starts, every node computes its priority and broadcasts it in its neighborhood. It also broadcasts the identities of its direct neighbors that it has discovered. Thus each node gets to know the topology information in its two-hop neighborhood.

Backbone seeds are also elected based on two-hop neighborhood information. When electing backbone seeds, we consider two factors. An ideal backbone seed should have high priority. In addition, to speed up the process of backbone construction, it is desirable to have backbone seed nodes chosen from an area of high node density so that more nodes can be covered quickly. We use node degrees as the indicator of node density. Considering these requirements, every node first compares its degree with the degrees of its neighbors based on the two-hop topology information. If its degree is the highest, it picks the neighbor with highest priority as backbone seed. Otherwise, it depends on nodes in other neighborhoods to pick backbone seeds.

Once backbone seeds are determined, SBC enters the second phase to grow the backbone to cover the whole network. If a node joins the backbone, it selects some of its neighbors to connect to remote nodes using the two-hop topology information. The algorithm executed by each recently selected coordinator for choosing neighboring coordinators is summarized in Figure 2. Function $selectNeighborCoordinator(i)$ selects coordinators from node i's one-hop neighbors. N_i^j denotes node i's neighbors which are within j hops from node i. $twohop_i^j$ denotes nodes i's two-hop neighbors which can be reached through i's one-hop neighbor j. $twohop_{min}$ and $twohop_{max}$ are the minimum and maximum number of two-hop neighbors reached through some direct neighbor respectively. $avgPriority_i$ is the average priority in node i's neighborhood.

Before selecting neighboring nodes, a coordinator takes a step to exclude some neighbors from consideration. By doing so, we attempt to avoid inclusion of two coordinators that are very close to each other. Recall that inclusion of nodes that are very close impairs the network performance because of severe interference and in addition does not help reduce much node redundancy. Because our model does not assume the knowledge of nodes' location, the distance has to be estimated. One way to do this estimation is by measuring the received signal strength and calculating the distance using the radio propagation formula. However, in practice, the radio transmission is affected by many factors, so this method is not reliable. Instead, because nodes in SBC know the topology information in two-hop neighborhood, we use the degree of common neighbors for the distance estimation. We define the *degree of overlapping* for a pair of nodes as the percentage of neighbors that are shared by the two nodes. In SBC, if the degree of overlapping is above a threshold, we consider the two nodes as being too close to be simultaneously considered as coordinators. This threshold is denoted by $overlapping_{th}$ in Figure 2. In later simulations, this threshold is set at 0.9.

When selecting neighboring coordinators, the neighbors with high priority are considered first. When considering high priority nodes, we try to balance the need for conserving energy and maintaining good network performance. This is controlled by G on line 6. When SBC chooses neighbor coordinators, it chooses a neighbor to connect with a moderate number of two-hop neighbors instead of trying to reach as many as possible. β controls the greediness of SBC. Using larger β, SBC reaches more two-hop neighbors through one neighbor. This is suitable when the traffic is light and only a few coordinators can handle it. When the traffic is heavy, SBC uses smaller β to allow more neighbor coordinators to provide more capacity. After high priority nodes are handled, if there are still unreachable two-hop neighbors, they must be connected through low priority nodes. To avoid affecting the stability of the backbone, low priority nodes are ordered by their priorities for selection as coordinators. Coordinators continue to be selected till all two-hop neighbors are connected

```
selectNeighborCoordinator($i$) {
  /* B is the set of selected neighbor coordinators.*/
  $B = \phi$;
  $avgPriority_i = \sum_{j \in N_i^1} priority_j / \mid N_i^1 \mid$;

  /* First consider neighbors with high priority.*/
  $G = (1 - \beta) * twohop_{min} + \beta * twohop_{max}$;
  $C = \{j \mid priority_j > avgPriority_i$ and
              $\mid twohop_i^j \mid > 0\}$;
  while $C \neq \phi$ do
      $\exists k, k \in C$ and $\mid twohop_i^k - G \mid$ is minimum;
      $B = B \cup \{k\}$;
      for ($m \in N_i^1$) do
          if $overlapping_{k,m} > overlapping_{th}$ then
              $C = C - \{m\}$;
          else
              $twohop_i^m = twohop_i^m - twohop_i^k$;
      $C = C - \{k\}$;

  /* Next consider nodes with low priority.*/
  $C = \{j \mid priority_j \leq avgPriority_i$ and
              $\mid twohop_i^j \mid > 0\}$;
  while $C \neq \phi$ do
      $\exists k, k \in C$ and $priority_k$ is maximum;
      $B = B \cup \{k\}$;
      for ($m \in C$) do
          if $overlapping_{k,m} > overlapping_{th}$ then
              $C = C - \{m\}$;
          else
              $twohop_i^m = twohop_i^m - twohop_i^k$;
      $C = C - \{k\}$;
}
```

Fig. 2. Algorithm for choosing neighboring coordinators.

through some one-hop neighbor. Here the overlapping rule is also applied.

After deciding on its neighboring coordinators, a coordinator broadcasts its decision to let the selected neighbors continue the coordinator selection process. Meanwhile, it also informs them of the information of existent coordinators. This information, combined with the two-hop topology information learnt before, enables the selected coordinators to make better decisions in their selection. In particular, this information is used in two ways. First the selected coordinators know that some remote nodes are already covered by other coordinators so they do not need to take care of them. Second, the above information is also used to enhance the connection among coordinators in SBC. A selected coordinator knows the other coordinators around it and prefers to choose the neighbors that can connect with other unreachable coordinators, which increase the robustness of the backbone because it allows more than one path between coordinators.

After coordinators connect the whole network, they agree on a service length. Non-coordinators can turn themselves off to conserve energy for the same length of time and let coordinators handle the communication in the network. To decide on the service length, we calculate the surviving time of node by considering its left energy and its energy consumption rate. We also calculate the time that node leaves its neighborhood considering its speed and transmission range. The smaller one of them becomes the service length.

C. An Example

Figure 3 shows a backbone constructed using the SBC algorithm. There are 100 nodes spread in an area of 1000m×1000m. SBC first chooses three nodes as the backbone seeds. Then the backbone expands from the seeds and nine additional coordinators are chosen. In Figure 3 directed edges point towards the newly selected coordinator and away from the coordinator responsible for selecting it. In the next step six additional coordinators are chosen. The final backbone consists 18 nodes. In the final figure the dashed edges connect coordinators that can hear from each other but were selected along different propagation paths.

III. PERFORMANCE EVALUATION

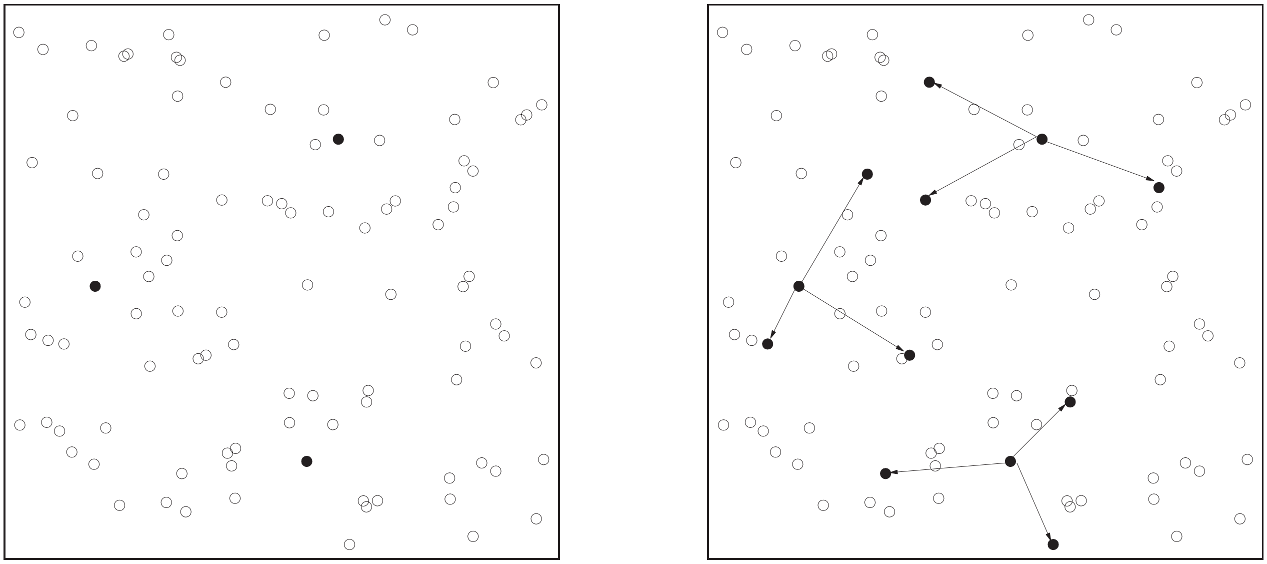
To evaluate the efficiency of SBC, we simulated SBC protocol in the ns-2.26 [15] network simulator. A series of tests were carried out with the following goals.

- *Energy and lifetime.* We want to see how much energy can be saved by using SBC and how the energy saving helps extend the lifetime of the network.
- *Network performance.* We want to find out how SBC affects the networking performance such as throughput.
- *Comparison with other techniques.* We compare the performance of SBC with other protocols, including 802.11, 802.11 power-saving mode (PSM) and GAF. 802.11 PSM is a supplement to 802.11 protocol. In 802.11 PSM, before sending a packet, a node broadcast the address of the receiver first so that the nodes other than the receiver could go to sleep during the period of data transfer. GAF is a backbone algorithm based on geographic information. GAF divides the network into grids of equal size. All nodes in any one grid have the same capability to communicate with all nodes in neighboring grids. Therefore only one node needs to be awake at any given time in each grid.

We test SBC under different conditions featuring a variety of traffic patterns, mobility levels, and node densities. The results which are described in detail in this section show that SBC allows more energy saving than other protocols while providing comparable networking performance.

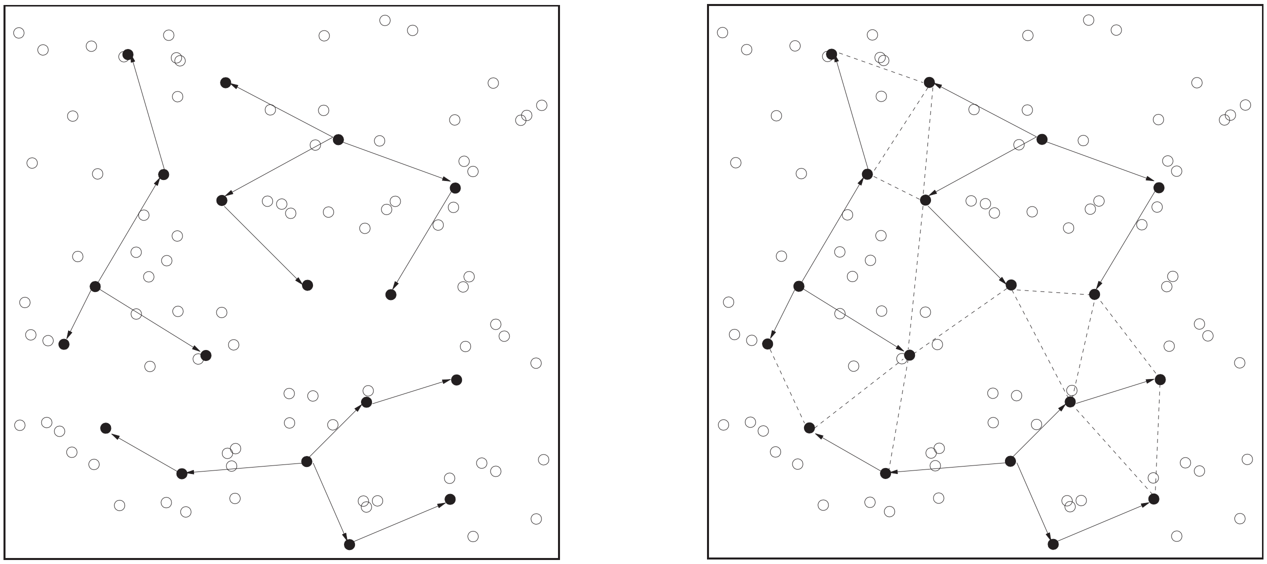
A. Simulation Setup

In the tests, we modelled a radio with 2 Mbps bandwidth and 250 meters nominal radio range. We choose AODV [10] as the routing protocol. The energy model is based on the work of [14], in which they measured the energy dissipation of an AT&T wireless WaveLan card and recorded the cost of 1.6w



(a) Seeds selected.

(b) Coordinators selected.



(c) Additional coordinators selected.

(d) Complete backbone.

Fig. 3. Backbone constructed by SBC.

when transmitting, 1.2w when receiving data, and 1.0w when idling. We ran every test in ten randomly generated scenarios. The result shown is the average of the ten runs.

Most of the tests are carried out on a 1000 meters by 1000 meters square and 100 routing nodes are placed randomly in the simulation region. SBC runs as standalone agents on the routing nodes, independent of AODV. Twenty additional nodes are placed on two full-height strips on the left and right side of the region to generate traffic. The width of the strips is 1/10 of the width of the test region. We choose this placement to ensure that the communication is carried by backbone. Two random nodes are selected respectively from each strip and are connected by a CBR flow. Every CBR flow sends and receives packets of 512 bytes. We vary the rate of the CBR flows to measure the performance of SBC under different traffic load. The overall CBR rate in the network varies from 10 pkts/s to 40 pkts/s, reflecting a data rate from 40 kbps to 160 kbps. We also vary the size of the square to study the affect of node density on SBC.

In the tests for mobile scenarios, routing nodes move at a random speed of between 0 to 20 meter/second. Traffic nodes do not move. The movement of the routing nodes follows the *random waypoint* model [2]. The routing nodes pause for a specified period of time and then move towards a randomly chosen location at a constant speed. The degree of mobility is characterized by the length of the pause period. We vary the pause time from 0 to 180 seconds.

B. Coordination Efficiency

We begin by comparing the efficiency of backbone formation by GAF and SBC in terms of the number of coordinators elected by GAF and SBC. Coordinator number indicates a protocol's ability to reduce node redundancy in the network. The smaller the number is, the more redundancy is removed. However, electing too few coordinators also brings about the danger of more congestion and harms the network performance. The test results are given in Figure 4. It shows that GAF elects more coordinators than SBC because GAF forces the nodes in the same grid to have the same connectivity, which restricts the effective transmission range of coordinators. SBC does not have the geographic restriction and the network connectivity is ensured by coordinator selection process. Although SBC uses fewer coordinators to cover the network, the network performance is not degraded as the later tests reveal. In some case, SBC even outperforms other protocols due to its comprehensive consideration of connectivity and energy conservation.

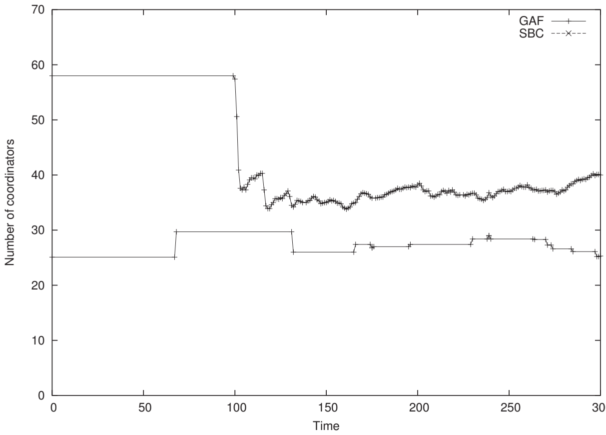
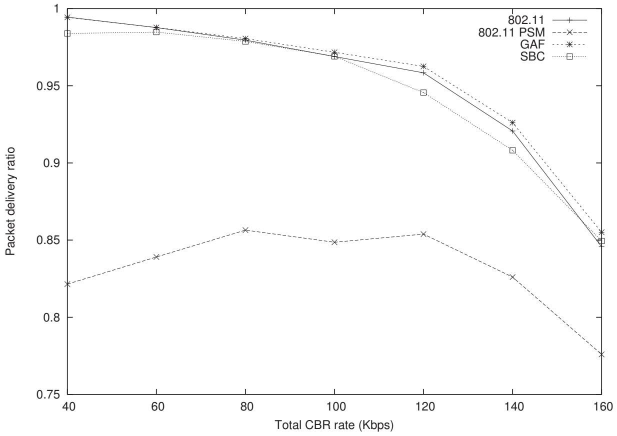


Fig. 4. The average number of coordinators elected by the protocols during the test duration.

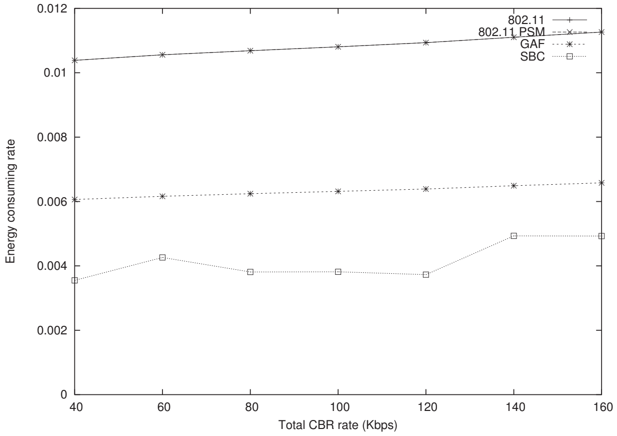
C. Network Capacity and Energy Conservation

One major concern of turning off nodes to conserve energy is how the network connectivity and capacity would be affected. Turning off all nodes achieves maximum energy saving, but also makes the network useless. On the other hand, a network with high level of node redundancy might fail to provide high throughput because of severe radio interference between nodes. The design object of SBC is to reduce the redundancy of nodes to a reasonable level to save energy and maintain adequate network capacity to facilitate communication in the meantime. In this section, we evaluate the performance of SBC in a series of scenarios featuring different traffic load to study how SBC affects the networking performance. Nodes do not move in this test.

We use the *packet delivery ratio* to measure the protocols' capability of maintaining the network capacity. We define the packet delivery ratio as the ratio of the number of packets received to the number of packets sent during the test duration. The tests were run for 300 seconds. Figure 5 shows the test results when the data rate changes from 40kbps to 160kbps. Figure 5a shows the packet delivery ratio of four protocols. All the protocols except 802.11 PSM keep satisfying network capacity when the traffic is light (under 120 kbps). When the traffic load increases above 140 kbps, the packet delivery ratio begins to decline rapidly because many packets are dropped due to aggravated radio interference. There is no significant difference in packet delivery ratio in all the cases, which shows proper use of backbone does not hurt the network capacity. At the end of the test, we recorded the remaining energy of nodes and calculated the energy consumption of every protocol, excluding the energy consumption of traffic nodes because they are always on. We define the *energy consumption rate* as the total energy consumption divided by test duration times the number of routing nodes. Energy consumption rate represents the average energy consumed by a routing node in one second.



(a) Packet delivery ratio.



(b) Energy consumption rate.

Fig. 5. Packet delivery ratio and energy consumption test under different traffic loads.

Figure 5b shows the energy consumption rate under different traffic load. Our results confirms the finding of [3], that is, 802.11 PSM does not achieve its goal. It uses as much energy as 802.11, but provides lower throughtput. In all the tests, SBC consumes less energy than other protocols. Under light traffic, SBC's energy consumption is 60% less than 802.11 and 38% less than GAF. Under heavy traffic, in which we use parameters to allow more coordinators to avoid congestion, SBC's energy consumption is 23% less than GAF. SBC allows more energy savings because it elects fewer coordinators and allows more nodes to go to sleep. When considering both packet delivery rate and energy consumption, SBC outperforms the other protocols.

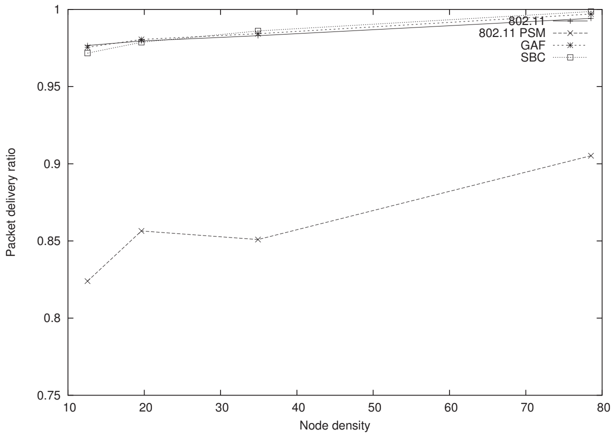
D. Effect of Node Density

Node density is another factor affecting efficiency of backbone. In network with low node density, more nodes should be kept awake to maintain the connectivity. On the contrary, network with high node density features high degree of node redundancy for power-saving protocols to exploit; thus allowing more energy savings. In this test, we vary the size of the simulation region to study SBC's adaptability to node density. We define node density as the average number of nodes within radio transmission range.

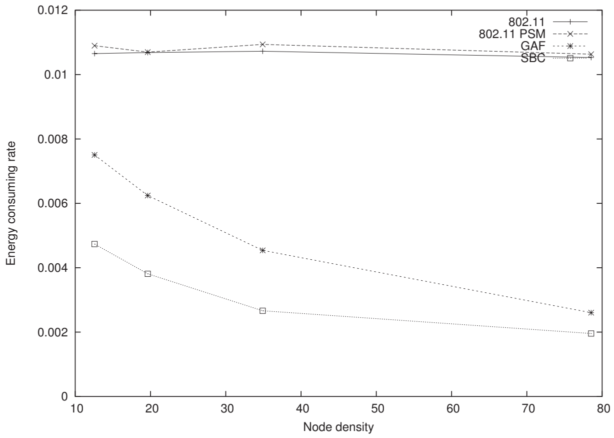
We vary the size of the test region to study the affect of node density. Figure 6a shows the results of the test. 802.11, GAF and SBC maintains good network capacity despite the change of node densities as shown in Figure 6a. Figure 6b shows the energy consumption. Density changes have an apparent affect on the backbone size and power conservation. In scenarios with high node density, backbone algorithm achieves greater power conservation. SBC still consumes less energy than GAF, although the difference decreases as the density increases.

E. Effect of Mobility

In this section we study SBC's performance in mobile scenarios. The movement of routing nodes follows the random waypoint model. In the test, routing nodes move at a constant speed chosen from between 0 m/s to 20 m/s towards a randomly chosen destination. After reaching the destination, node pauses for some specified time, then moves towards another randomly chosen location. We vary the pause time to measure SBC's performance under different degrees of mobility. The whole test lasts for 300 seconds.

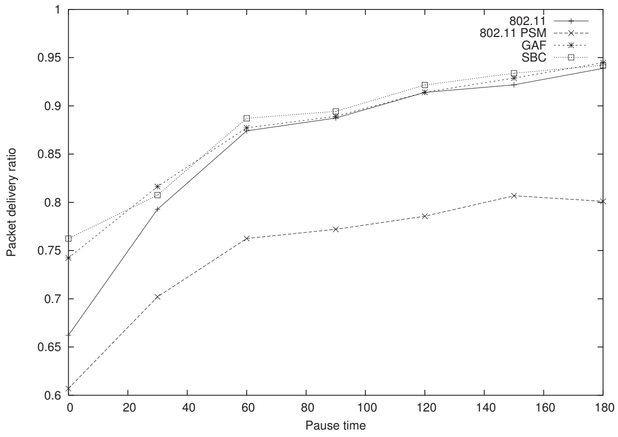


(a) Packet delivery ratio.

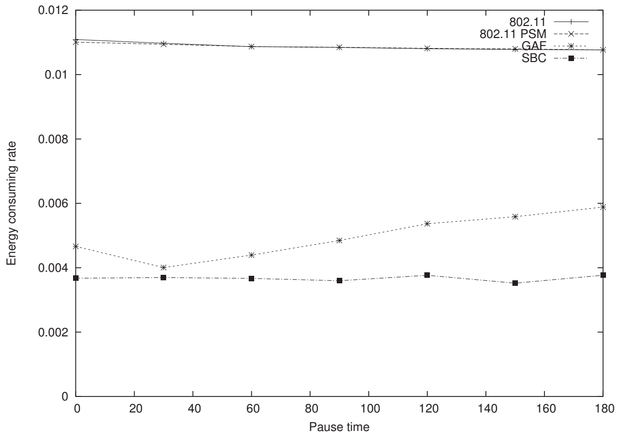


(b) Energy consumption rate.

Fig. 6. Packet delivery ratio and energy consumption test under different node density. Traffic load is 20pkts/s (80kbps/s).



(a) Packet delivery ratio.



(b) Energy consumption rate.

Fig. 7. Packet delivery ratio and energy consumption test under different movement patterns. The traffic load is 20pkts/s (80kbps).

Figure 7a is the packet delivery ratio when the pause time varies from 0 to 180 seconds. It shows that under high degree of node mobility, backbone protocols actually provide better throughput than 802.11 because routes in backbone consist of stable coordinators and suffer less from node mobility. As described in the algorithm, SBC's design carefully considers the affect of movement on the stability of coordinators and prefers nodes that are stationary or moving at a slow speed. So backbone formed with SBC can remain valid for a long time and thus reduce the chance of route failure due to nodes moving out of radio range. SBC also exhibits good energy saving property as shown in Figure 7b. SBC consumes less energy than other protocols. Despite the degree of mobility, the energy consumption is quite stable, which indicates that SBC can find out ideal coordinators with low mobility and does not increase the size of backbone significantly.

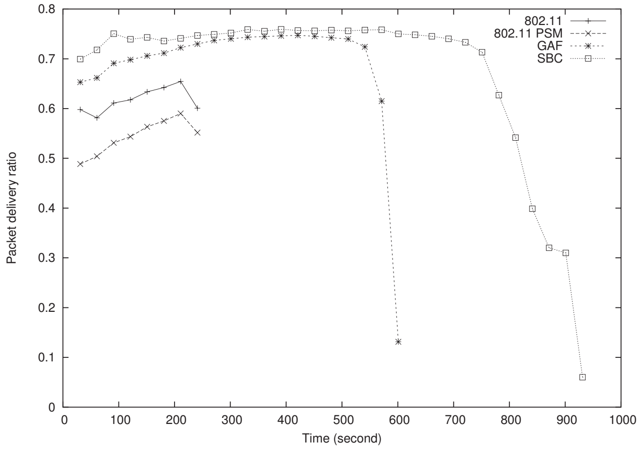
F. Extending Network Life

Energy conservation is meaningful only when it helps extend the network lifetime. An undesirable situation is one in which energy saving is not uniformly distributed among nodes so that connectivity is confined to a small area because nodes connecting some areas run out of energy early. We have shown that SBC can save significant energy in the tests above. Here we test the extent to which the energy saving translates into extended network lifetime. In this test, routing nodes are given limited energy and the test continues until nodes run out of energy or no packets are delivered for a sufficiently long time, which we consider as the sign that the surviving nodes cannot connect the network effectively.

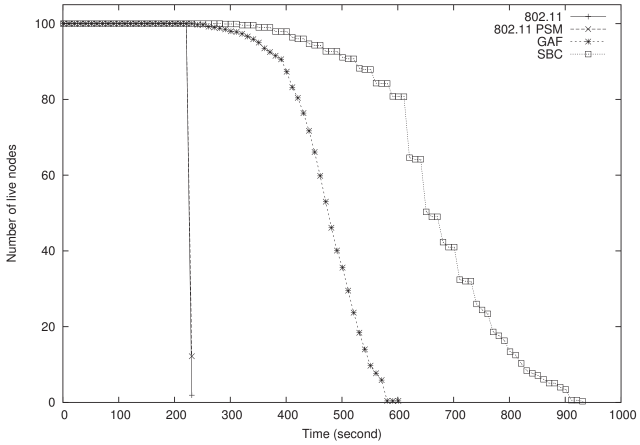
Figures 8 and 9 show the results in dynamic and stationary scenarios. The packet delivery ratio is measured every 30 seconds. Nodes under 802.11 and 802.11 PSM run out of energy around the same time, while the lifetime under backbone protocols is more than doubled. SBC extends the lifetime by another 20% beyond that of GAF. This indicates that the energy saved by SBC is properly distributed among nodes to extend the life of the whole network. Because backbone does not affect the routing decision, some regions bear heavier traffic and nodes in that region run out of energy sooner than other nodes. Thus the improvement to network life is not proportional to the energy saving. It is noticeable that the life extension in dynamic scenarios is greater than in stationary scenarios. This can be explained by the fact that in dynamic scenario if nodes in one area run out of energy, other nodes could possibly move into that area and thus the connectivity continues to be maintained. In static scenario, an area becomes void if nodes in the area run out of energy. We also record the number of live nodes in the tests every 10 seconds. The results show that nodes in SBC last for a longer period than GAF due to greater energy saving.

IV. RELATED WORK

Energy conservation is a crucial issue in ad hoc networks. Thus, lots of research besides topology control is targeted at reducing energy consumption.



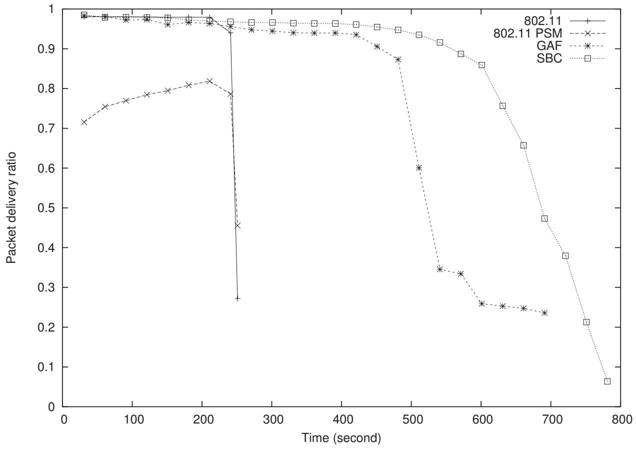
(a) Packet delivery ratio changes over time.



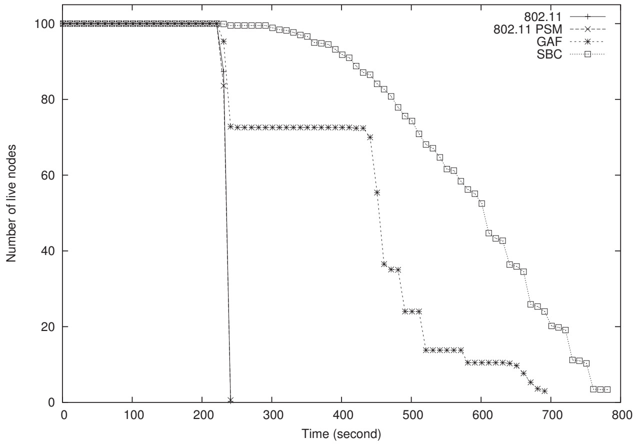
(b) The number of live nodes over time.

Fig. 8. Network life test under high mobility (pause = 0). The traffic load is 20pkts/s (80kbps).

Designing energy-friendly routing protocols has been the focus of much research. The well established ad hoc routing protocols, such as AODV used in our experiments, do not take energy into consideration and usually pick the shortest path to the destination. However, shortest paths are not always the most energy-efficient paths. In [9], the authors described a routing protocol which finds the power consumption of several paths and picks a path whose consumption is under a threshold and on which the nodes have energy above a threshold. Thus, this approach both saves energy and distributes energy consumption fairly among nodes. In [12] it is shown how the transmitting power can be adjusted to form a path with minimum power consumption. Modifications to DSR protocol to make it energy-aware are described in [5]. Suggested changes include computing energy cost, controlling transmit power, discovering minimum energy route, etc. In experiments, all these protocols show good results in reducing power consumption. However, we believe that turning off unused nodes is the ultimate way to save energy in ad hoc networks considering the significant energy consumption even



(a) Packet delivery ratio changes over time.



(b) The number of live nodes over time.

Fig. 9. Network life test in static scenarios. The traffic load is 20pkts/s (80kbps).

when a node is in idle state. But, since SBC is independent of the routing protocols, it can be used in combination with those energy-efficient routing protocols so that energy consumption among backbone nodes is distributed uniformly.

Besides constructing backbone, some other approaches also save energy by turning off nodes. However, they operate at MAC level. The PAMAS power saving medium access protocol [13] uses a second channel to detect nearby communication. In PAMAS, a node turns off its radio when it is not involved in the upcoming communication. 802.11 power saving mode [17] is another MAC-level energy saving measure. Because both of them run at the MAC level, and have a limited view of network topology, nodes are turned on and off at a short interval, usually the time for transmitting a packet. Backbone methods allow more energy savings than MAC layer methods because they use more topology information to construct a backbone that is stable for a longer period and thus nodes can sleep longer to save more energy.

Finally, SBC can be used with other power-saving measures. In [6] Feeney presented a simple asynchronous approach in which nodes independently establish a periodic sleep/wake cycle. Neighbors communicate with each other when their wake periods overlap. In [21] Zheng et al. elaborate on the asynchronous approach and formulates the optimal wake-up schedule based on combinatorics. Such asynchronous schedule can be applied to the backbone nodes to enable the backbone to sleep when there is no communication.

V. CONCLUSIONS

This paper presented *SBC*, an algorithm of constructing backbone in ad hoc wireless network for energy conservation. SBC employs a different procedure from other backbone construction algorithms. In SBC, backbone construction starts from backbone seeds and propagates outwards until the whole network is swept. Topology information is transferred during this process. The later backbone decisions are made based upon more knowledge about the network, which leads to a more efficient backbone. Our experiments with SBC show a superior capability of conserving energy in comparison to 802.11, 802.11 PSM, and GAF. In conclusion, SBC constructs backbones that are smaller, it results in energy savings that translate into extended network lifetimes, and at the same time SBC provides satisfactory network performance.

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