Efficient Backbone Construction Methods in MANETs Using Directional Antennas*

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Abstract

In this paper, we consider the issue of constructing an energy-efficient virtual network backbone in mobile ad hoc networks (MANETs) for broadcasting applications using directional antennas. In directional antenna models, the transmission/reception range is divided into several sectors and one or more sectors can be switched on for transmission. Therefore, data forwarding can be restricted to certain directions (sectors), and both energy consumption and interference can be reduced. We develop the notation of directional network backbone using the directional antenna model, and form the problem of the directional connected dominating set (DCDS) which is an extreme case of the directional network backbone using an unlimited number of directional antennas. The minimum DCDS problem is proved to be NP-complete. A localized heuristic algorithm for constructing a small DCDS is proposed. Performance analysis includes an analytical study in terms of an approximation ratio and a simulation study on the proposed algorithms using a custom simulator.

1 Introduction

Broadcasting is the most frequently used operation in mobile ad hoc networks (MANETs) for the dissemination of data and control messages in the preliminary stages of some other applications. Usually, a wired network backbone is constructed for efficient broadcasting, where only selected nodes that form the backbone forward data and the entire network receives it. The dominating set (DS) has been widely used in the selection of an efficient virtual network backbone. A set is dominating if every node in the network is either in the set or a neighbor of a node in the set. When a DS is connected, it is called a connected dominating set (CDS); that is, any two nodes in the DS can be connected through intermediate nodes from the DS. The CDS as a connected virtual backbone has been widely used for efficient broadcasting in MANETs. In [7] it is demonstrated that any broadcast scheme based on a backbone of size proportional to the minimum CDS guarantees a throughput within a constant factor of the broadcast capacity.

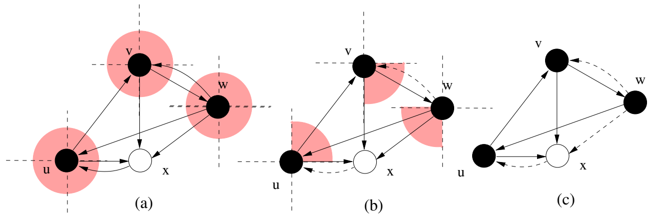

Figure 1. (a) a network backbone, (b) a directional backbone, (c) a DCDS.

In a directed graph, the set in the virtual network backbone for broadcasting is called the connected dominating and absorbant set [13]. If two nodes are connected by a directed edge, the start node is a dominating neighbor of the end node, and the end node is an absorbant neighbor of the start node. In a connected dominating and absorbant set, nodes in the set are strongly connected, and each node that is not in the set has at least one dominating neighbor and one absorbant neighbor in the set. As shown in Figure 1 (a), black nodes $\{u, v, w\}$ form a connected dominating and absorbant set. The set $\{v, w\}$ is also strongly connected, and all the other nodes u and x can be dominated by it. However, x can only reach u which is not in the set, thus the broadcast cannot achieve full coverage when the source is x. $\{v, w\}$ is not a connected dominating and absorbant set.

Recently, the directional antenna model [8] was devel-

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oped and implemented in various applications. With the help of switched beam and steerable beam techniques, antenna systems of wireless nodes can perform directional transmission and/or reception. A common directional antenna model involves dividing the transmission range of a node into K identical sectors, and one or more sectors can be switched on to transmit/receive. Compared with omnidirectional antenna systems, the use of directional antenna systems helps to improve channel capacity as well as conserve energy since the signal strength towards the direction of the receiver can be increased. Due to the constraint of the signal coverage area, interference can also be reduced.

In this paper, we put forth the *directional network backbone* concept. When using a directional antenna model, each node divides its omnidirectional transmission range into K sectors. Parts of them can be selected to be switched on for transmission. We assume that all nodes use a directional antenna for transmission and an omnidirectional antenna for reception. A directional virtual network backbone is defined as a set of selected nodes and their associated selected transmission sectors. Only the nodes in the backbone forward data towards their selected transmission sectors. The entire network receives the data, assuming the absence of interference. Figure 1 illustrates the concept. The black nodes in (a) are a connected dominating and absorbant set which forms the network backbone using omnidirectional antennas. (b) shows a directional backbone in black nodes and their associated shaded transmission sectors with each spanning $90°$. We can see that data from any node in the backbone can reach any other node in the entire network. Note that in order to get a white node to reach a black node, only one sector must be switched on for transmission. The total number of the selected sectors is 3 among black nodes in this example, less than the original one in (a) which is 12. We consider in this paper a general model where sectors are not necessary aligned, unlike the case shown in Figure 1. Note that no GPS assistance is necessary. Each node sends out "Hello" messages K times to the K directions and accomplishes the directional neighborhood discovery.

Inspired by the method of using a CDS to construct an efficient virtual network backbone, we propose a notion of *directional connected dominating set* (DCDS) using the directional antenna model, which is a special case of the directional network backbone where K is infinite. In a directed graph, a DCDS is a set of selected nodes and their associated selected edges. Each selected node can reach all other nodes, including non-selected nodes, via edges in DCDS. In addition, each non-selected node has an absorbant neighbor in the DCDS. We can see that with only nodes in the DCDS forwarding, the entire network will receive the broadcast data. Figure 1 (c) shows the DCDS in dark nodes and solid edges. There are 5 forwarding edges. This definition also works for undirected graphs since they are special cases of directed graphs. When in practice the number of directional antennas of each node is finite, we can first find the DCDS. Then, each selected node simply switches on for the corresponding sectors which contain selected edges. We also develop a sector optimization algorithm.

A minimum DCDS problem is to find one with the least selected edges which is proved to be NP-complete in this paper. In contrast to the connected dominating and absorbant set, here we try to reduce not forwarding nodes, but forwarding edges. This guarantees the smallest energy consumption in the application of broadcasting using directional antennas. Note that the energy consumption in any direction is fixed. The minimum DCDS problem is not a trivial extension of the minimum CDS problem. This is because the nodes in the minimum DCDS may be more than the nodes in the minimum CDS of a graph.

This paper focuses on using the DCDS concept to construct an energy efficient directional backbone. We will focus on the following issues: (1) *The directional network backbone problem.* We put forth the concept of directional virtual network backbone using directional antennas in MANETs. (2) *The DCDS problem.* We develop the DCDS problem which is an extreme case of the directional virtual network backbone problem, and prove its NP-completeness. (3) *Heuristic localized solutions to the minimum DCDS problem.* We propose an approach to select forwarding nodes and edges for the DCDS and prove that it has a probabilistic approximation ratio. (4) *Optimization of transmission sectors.* We present an optimization algorithm to determine transmission sectors depending on the designated edges from DCDS when K is finite. (5) *Performance analysis.* We conduct performance analysis through analytical and simulation studies on the proposed solutions.

2 Related Works

2.1 General CDS Construction

The minimum CDS (MCDS) problem is NP-complete. Global solutions [4] are based on global state information and are expensive. Among distributed solutions, the tree-based CDS approach [11] requires network-wide coordination, which causes slow convergence in large scale networks. The cluster-based approaches in [16] exhibit sequential propagation. The status (clusterhead/non-clusterhead) of each node depends on the status of its neighbors, which in turn depends on the status of neighbors' neighbors and so on.

Localized CDS formation algorithms require network-wide coordination or sequential propagation and include Wu and Li's marking process (MP) [15] and self-pruning rule, Rule k [2]. In Rule k, a node can be withdrawn from the CDS if all of its neighbors are interconnected via k ($k \geq 1$) nodes with higher priorities. The probabilistic approximation ratio of Rule k is $O(1)$. Wu and Dai further proposed a localized CDS formation [14], which can be viewed as a generic framework for several other existing broadcasting algorithms.

2.2 Directional Antennas

The most popular directional antenna model is ideally sectorized, as in [6], where the effective transmission range of each node is equally divided into K non-overlapping sectors, and one or more such sectors can be switched on for transmission or reception. Another directional antenna model is the adjustable cone [10] using the steerable beam system. The channel capacity when using directional antennas can be improved because the directional transmission increases the signal energy towards the direction of the receiver. Also, the nodes can communicate simultaneously without interference.

Some probabilistic approaches for broadcasting using directional antennas are proposed. In [1], a broadcast scheme is proposed using directional antennas to reduce redundancy. In [6], schemes are developed to switch off transmission beams towards known forward nodes or designate only one neighbor as a forward node in each direction. Several centralized algorithms were proposed in [12], where a tree is built to connect all receivers with a minimal number of forward nodes and beam widths. Only two localized deterministic schemes were proposed [9, 10]. In [3], Dai and Wu proposed a deterministic localized broadcast protocol using directional antennas, where directional self-pruning (DSP) is developed to reduce transmission directions. However, DSP is used for efficient broadcasting where the source is known. All of the above schemes assume an omnidirectional reception mode.

3 Directional Connected Dominating Set

In the directional antenna model, there is an edge connecting node x to node y only if y is within the transmission range of x, and y is in the sector of x which is switched on. We assume when using the omnidirectional model, that the given directed graph is strongly connected. The given graph can be an undirected graph, also, since it is a special case of a directed graph with symmetric connectivity, i.e., an edge $(u \rightarrow v)$ exists *iff* $(v \rightarrow u)$.

3.1 Directional Network Backbone

A directional backbone is a subset of nodes and their selected sectors such that each node in the backbone can reach any nodes in the original network through forwarding along the selected sectors. In addition, each node that is not in the backbone can select a sector to reach a backbone neighbor. Note that the selection of a directional backbone may destroy the symmetric connectivity (of a given undirected graph), since the selection of $(u \rightarrow v)$ does not coincide with the selection of $(v \rightarrow u)$. That is, an undirect graph can become a direct one after the selection.

As shown in the example in Figure 1 (b), the directional backbone contains three dark nodes and their selected sectors. For the nodes not in the directional backbone, they are not used for forwarding. They are involved in the transmission only if they are the source. Each of them can use the omnidirectional antennas to broadcast for simplicity, or detect the sector which can reach a forwarding node and turn on the corresponding sector for transmission. Note that the derived graph of the directional backbone is a connected dominating and absorbant set. Thus there exists at least one such sector for each nonforward node.

The minimum directional backbone is the one with the minimum number of selected sectors. When $K = 1$, it is the traditional minimum connected dominating and absorbant set problem, where each sector corresponds to a node. We consider here another extreme case when $K = \infty$, where each edge becomes a sector.

3.2 Directed Connected Dominating Set

A CDS is usually used to construct an efficient virtual network backbone in MANETs. Inspired by this, we define a directional connected dominating set (DCDS) using directional antenna models, to approximate the directional network backbone. The main idea is that in the directional virtual network backbone concept, if the number of sectors is infinite, selecting of switched-on sectors equals selecting of forwarding edges. Each outgoing edge of a node has a corresponding directional antenna and can be viewed as a transmission sector. In a directed graph, a directed edge from node u to node v is denoted as $(u \rightarrow v)$, u is v's *dominating neighbor*, and v is u's *absorbant neighbor*. This edge is u's *dominating edge*, and v's *absorbant edge*.

Definition 1: **(DCDS)** In a strongly connected directed graph $G = (V, E)$, consider a subset of nodes $V^{'} \subseteq V$ and three subsets of edges $E^s \subseteq \{(u \rightarrow v)|u, v \in V^{'}\}$, $E^d \subseteq \{(u \rightarrow v)|u \in V^{'}, v \in V - V^{'}\}$, and $E^a = \{(u \rightarrow v)|u \in V - V^{'}, v \in V^{'}\}$, such that

1. $(V^{'}, E^s)$ is a strongly connected graph.
2. For $v \in V - V^{'}$, there exists u with $(u \rightarrow v) \in E^d$.
3. For $u \in V - V^{'}$, there exists v with $(u \rightarrow v) \in E^a$.

$(V^{'}, E')$ is called a directional connected dominating and absorbant set where $E^{'} = E^s \cup E^d$ are the selected dominating edges of $V^{'}$.

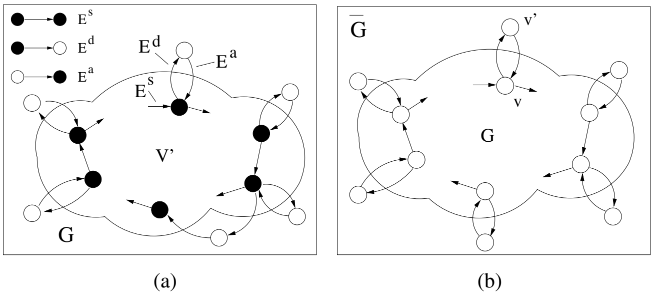


Figure 2. (a) A DCDS of G, $(V', E^s \bigcup E^d)$, (b) the proof of Theorem 1.

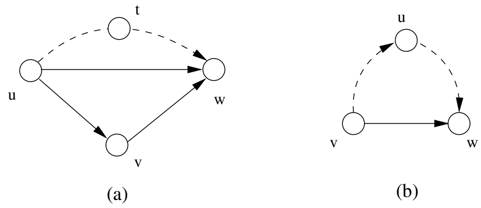


Figure 3. Directed replacement paths in (a) node coverage, and (b) edge coverage.

$G' = (V, E^s \cup E^d \cup E^a)$ is a strongly connected directed subgraph of G and V' is a connected dominating and absorbant set in G, as shown in Figure 2 (a). DCDS constructs a virtual network backbone by designating not only forwarding nodes, but also forwarding directions (edges). If not in the DCDS, the source node uses its dominating edge (in E^a) to send data to the backbone. Since compared with other forwardings this one-hop data transmission appears only once for a broadcasting, we can exclude these source-purpose edges, E^a, from the DCDS, and focus exclusively on forwarding-purpose edges, $E' = E^s \cup E^d$.

Definition 2: **(The Minimum DCDS)** The minimum DCDS of a given graph is the one which has the smallest number of selected edges $|E'|$.

Theorem 1 *The minimum DCDS problem is NP-complete.*

We can consider any strongly connected graph G as in Figure 2 (b), constructing a new graph $\overline{G}$ by adding an "image" vertex v' for each vertex v in V and two edges $(v \rightarrow v')$ and $(v' \rightarrow v)$, $(v \rightarrow v') \in E^d$ and $(v' \rightarrow v) \in E^a$. Then if we find a strongly connected subgraph in G with the minimal edges and denote the edges in the subgraph as E^s, then $(V, E^s \bigcup E^d)$ is the minimum DCDS for $\overline{G}$. The problem of finding the smallest strongly connected subgraph in terms of number of edges in a given strongly connected graph (G) is NP-complete [5]. Therefore, finding E^s is NP-complete. So is finding $E^s \bigcup E^d$.

Using omidirectional antennas, the traditional connected dominating and absorbant set in directed graphs only focuses on the number of forwarding nodes. However, in DCDS, with the help of directional antennas, the number of forwarding edges determines the consumed energy. Hence, we are trying to find the DCDS with minimal forwarding edges. It is obvious that when K is infinite, the minimum DCDS corresponds to the minimum directional backbone. When K is finite, we can use a two-phase approach to approximate the minimum directional backbone. The first phase involves finding the minimum DCDS. In the second phase, each forwarding node switches on certain sectors covering all of its selected edges. A simple way to do this is to switch on any sector that contains at least one selected edge. If the sectors of the directional antennas of each node are not necessarily aligned, an optimized sector selection algorithm can be designed which will be discussed in the next section. Therefore, as shown in Figure 1, from the result of (c), the directional backbone as in (b) can be achieved.

4 Localized Heuristic Solution

We propose a heuristic localized approach to find the minimum DCDS in directed graphs. A localized approach relies only on local information, i.e., properties of nodes within its vicinity. In addition, unlike the traditional distributed approach, there is no sequential propagation of any partial computation result in the localized approach. The status of each node depends on its h-hop topology only for a small constant h, and is usually determined after h rounds of "Hello" message exchange among neighbors. A typical h value is 2 or 3. We use node priority to break the tie and avoid simultaneous node withdrawal. Node priority is unique. Node IDs and other node properties can be used as node priority, such as energy level or node degree. We assume that the priority of node u is $p(u)$ based on the alphabetic order, such as $p(u) > p(v) > p(w) > p(x)$ in Figure 1. No location information is needed.

4.1 Node and Edge Coverage Conditions

In [14], the coverage condition for CDS construction for undirected graphs states that a node v is unmarked if, for any two neighbors, u and w of v, a replacement path exists connecting u and w such that each intermediate node on the path has a higher priority than v. The coverage condition generates a CDS since for each withdrawn node, there must exist a replacement path for each pair of its neighbors to guarantee the connectivity. Nodes in the replacement path can also cover neighbors of the withdrawn node.

The edge coverage condition (ECC) algorithm for DCDS modifies the coverage condition concept to directed graphs. The main idea is to first select the forwarding nodes using the node coverage condition, then each marked node applies the edge coverage condition to select forwarding edges. Note that although the procedure contains two phases, each node only collects the neighborhood information (topology and node priority) once in the beginning. That is, further information exchange about node status (marked or unmarked) is not necessary.

Node Coverage Condition. *Node v is unmarked if, for any two dominating and absorbant neighbors, u and w, a directed replacement path exists connecting u to w such that (1) each intermediate node on the replacement path has a higher priority than v, and (2) u has a higher priority than v if there is no intermediate node.*

The node coverage condition is different from the coverage condition in [14] in that when there is no intermediate node on the replacement path, v can be unmarked only if $p(u) > p(v)$. Obviously, the node coverage condition is stronger than the original coverage condition. Thus, the marked nodes generated by it form a connected dominating and absorbant set. We will show later why this extra condition is necessary. Figure 3 (a) shows two types of directed replacement paths from u to w using the node coverage condition. When there is at least one intermediate node t, then $p(t) > p(v)$. Otherwise, when u is directly connected to w, $p(u) > p(v)$ is necessary. Then, we use the same concept to unmarked edges. First, we introduce the priority assignment method for edges.

Edge Priority Assignment. *For each edge $(v \rightarrow w)$, the priority of this edge is $p(v \rightarrow w) = (p(v), p(w))$.*

Thus, the priority of an edge is a tuple based on the lexigraphic order. The first element is the priority of the start node of this edge and the second one is the priority of the end node. Therefore, there is a total order for all the edges in the graph and the edge coverage condition can be applied on every edge.

Edge Coverage Condition. *Edge $(v \rightarrow w)$ is unmarked if a directed replacement path exists connecting v to w via several intermediate edges with higher priorities than $(v \rightarrow w)$.*

Algorithm 1 ECC algorithm

1. Each node determines its status (marked/unmarked) using the node coverage condition.
2. Each marked node uses the edge coverage condition to determine the status of its dominating edges.

Figure 3 (b) shows the directed replacement path for edge $(v \rightarrow w)$. In this case, both the intermediate edges ($(v \rightarrow u)$ and $(u \rightarrow w)$) have higher priorities than edge $(v \rightarrow w)$. We still use Figure 1 to illustrate the ECC algorithm. The forwarding nodes are marked as in (b). Node x is unmarked since for neighbor pair v, u, there is a replacement path $(v \rightarrow w \rightarrow u)$ with $p(w) > p(x)$ (case (1) of the node coverage condition); for neighbor pair w, u, there is a replacement path $(w \rightarrow u)$ with $p(w) > p(x)$ (case (2) of the node coverage condition). The dominating edges of the marked nodes are shown as solid lines. Note that the dominating edges of unmarked nodes can be omitted. Then each marked node applies the edge coverage condition to determine the status of each dominating edge. In (c), marked edges are shown in solid lines. For example, the edge $(w \rightarrow v)$ with priority $(p(w), p(v))$ is unmarked because of the replacement path $(w \rightarrow u \rightarrow v)$ with higher edge priorities $(p(w), p(u))$, $(p(u), p(v))$. The edge $(w \rightarrow x)$ with priority $(p(w), p(x))$ is unmarked because of the replacement path $(w \rightarrow u \rightarrow v \rightarrow x)$ with higher edge priorities $(p(w), p(u))$, $(p(u), p(v))$, and $(p(v), p(x))$. Note that when these two edges are unmarked, only 2 hops local information is necessary.

Theorem 2 *Given a directed graph $G = (V, E)$, V' and E' generated by ECC constructs a DCDS.*

Proof If we prove that for any two nodes $s \in V'$ and $d \in V$, there is a path with all intermediate nodes and edges only from V' and E', we prove that (V', E') is a DCDS. Note that s and d can be either marked or unmarked nodes. In ECC, after step 1, V' is a dominating and absorbant set, thus there are paths connecting s to d with intermediate nodes all marked, as in Figure 4 (a). We use set S_P to denote these paths. Now we prove by contradiction. Suppose any path in S_P connecting s to d has at least one unmarked edge (with a cross (X) on it). Thus a ring area containing only unmarked edges exists as an "outer rim" of node d, as the gray area W in Figure 4 (a). We assume that edge $(u \rightarrow w)$ is the edge with the highest priority in area W. Since $(u \rightarrow w)$ is unmarked, there must exist some replacement paths connecting u to w via edges with higher priorities than $p(u \rightarrow w)$. We use R_P to denote these replacement paths.

There are two cases for the status of nodes on paths in R_P. Case 1: There is at least one path in R_P with only marked nodes on it. Then we assume edge $(u' \rightarrow w')$ is the edge on this path and also in W. Therefore, $p(u' \rightarrow w')$ is larger than $p(u \rightarrow w)$. This contradicts the assumption that $(u \rightarrow w)$ is the highest priority edge in area W. Case 2: There is at least one unmarked node on each path in R_P. As shown in Figure 4 (b), these unmarked nodes form a rim W'. We then assume node u' has the highest priority in W'. Since u' is unmarked, there must exist a replacement

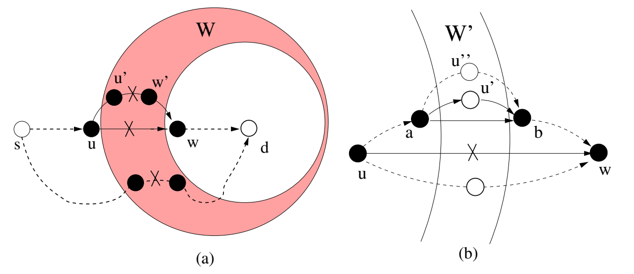


Figure 4. Node and edge coverage condition.

path, P_a, for it is based on the node coverage condition. (1) There is at least one node on P_a, node u'', which is also in W' (otherwise there is a path in R_P with only marked nodes). The priority of u'' is higher than that of u', which contradicts the assumption that u' is the highest one in W'. (2) There is no intermediate node on P_a. The dominating neighbor of u' is connected to its absorbant neighbor on P_a; $(a \rightarrow b)$ exists. If $a \neq u$ or $b \neq w$, u' can be removed from P_a. If $a = u, b = w$, since u' is unmarked, $p(a) = p(u) > p(u')$, which contradicts the assumption that $p(u' \rightarrow w) > p(u \rightarrow w)$ (edge $(u' \rightarrow w)$ is on P_a). All of the contradictions above show that there exists a path connecting s to d with only marked nodes and edges. □

From the above proof we can see why the second condition of the node coverage condition is necessary. In Figure 4 (b), when $a = u$, and $b = w$ and $p(u') > p(a) = p(u)$ (thus edge $(u \rightarrow w)$ can be unmarked based on the edge coverage condition), if u' can be unmarked based on the node coverage condition without the necessary that $p(a) = p(u) > p(u')$ as case (2) of the node coverage condition, u' and edge $(u \rightarrow w)$ are unmarked simultaneosly.

Figure 6 shows a large scale example in a 10×10 area. The number of nodes is 30, and the transmission range is 3. The resultant DCDS is shown as dark nodes and dark arrows. In the resultant graph, there are 13 forwarding nodes and 47 forwarding edges. All the directed neighbors of node 21 are connected to one another. For example, node 21 has the highest priority (the larger the node ID, the higher the node priority) in its local area. Thus, using the node coverage condition, it is a forwarding node. The same can be said for node 23.

4.2 Sector Optimization (SO)

After the directional edges are determined for each forwarding node, its transmission directions can be calculated based on the given number of sectors K. We also assume that the sectors of the directional antenna of each node are not necessarily aligned. We can develop an optimization algorithm to let each node circumgyrate its antennas to minimize the number of its switched-on sectors.

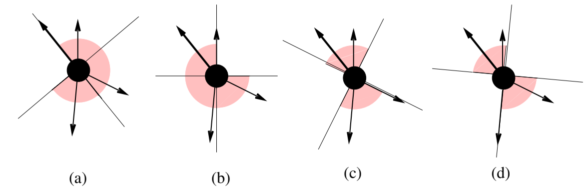


Figure 5. Illustration of SO.

Algorithm 2 SO algorithm

Align the edge of one sector to each selected forwarding edge, and determine the one with the smallest number of switched-on sectors.

In Figure 5, $K = 4$, and the forwarding node has four forwarding edges. The antenna sectors are circumgyrated to align with each edge. In cases (c) and (d) there are a smaller number of switched-on sectors. The time complexity is the number of forwarding edges, $|E'_v|$ (dominating edges of node v in E').

We can easily show that the node coverage condition produces a smaller CDS than a known condition called Rule k [2]. Our previous work has proven that the expected number of marked nodes in Rule k is bounded by $O(1)|CDS_{opt}|$. This is also an upper bound for the total number of marked nodes in ECC algorithms. When an ideally sectorized anntenna model with K sectors is used, the expected number of transmission directions is $O(K)|CDS_{opt}|$. Note that the above argument is before the edge coverage condition is applied.

Theorem 3 *Given an ideally sectorized antenna model with K sectors, the average performance of the ECC algorithm is $O(K)$ times that in an optimal solution in random MANETs.*

5 Simulation

We evaluate the proposed ECC algorithm by comparing the DCDS generated by the proposed algorithms with the traditional CDS using omnidirectional models in terms of the number of forwarding nodes, forwarding edges, and switched-on sectors. We use two approaches to generate CDS, Rule k [2] and coverage condition (Generic) [14].

5.1 Simulation Environment

In our simulation, n nodes are randomly placed in a restricted 100×100 area. The tunable parameters in the sim-

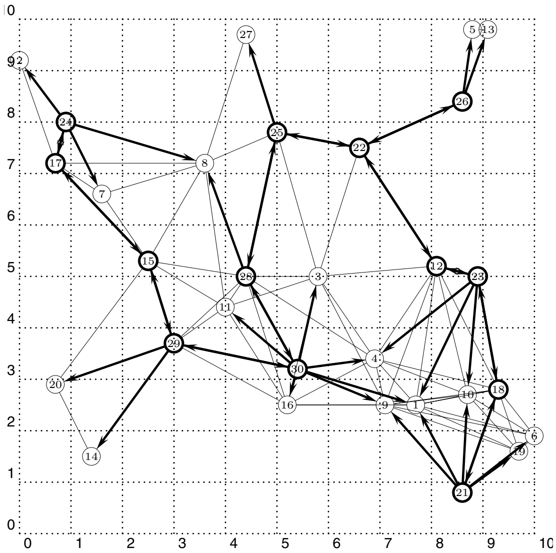
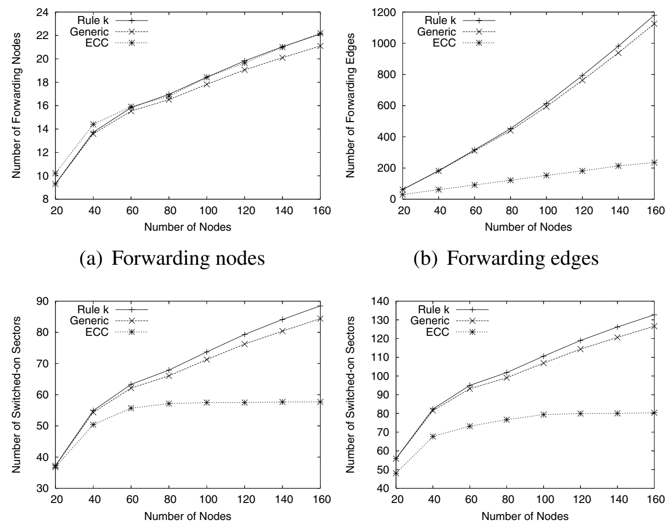


Figure 6. An example of DCDS by ECC.



(a) Forwarding nodes (b) Forwarding edges

(c) Switched-on sectors ($K = 4$) (d) Switched-on sectors ($K = 6$)

Figure 7. Comparison of Rule k, Generic, and ECC in directional graphs.

ulation are as follows. (1) The number of nodes n. We vary the number of deployed nodes from 20 to 160 to check the scalability of the algorithms. (2) The transmission range r. In order to generate directed graphs, each node randomly picks its transmission range from 20 to 40. (3) The number of sectors of the antenna pattern K. We use 4 and 6 as the values of K. (4) The number of hops h. In coverage conditions, 2, 3, or 4 hops local information is collected.

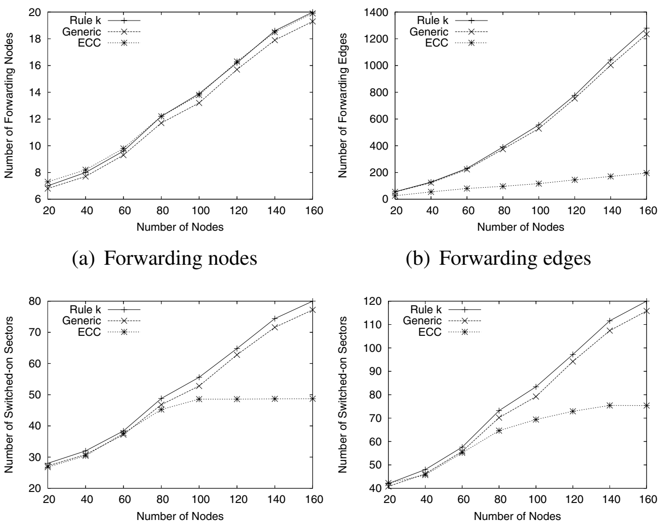
5.2 Simulation Results

Figure 7 shows the comparison of Rule k and Generic which generate the CDS, and the ECC algorithm which generates the DCDS. In (a) the number of forwarding nodes of ECC is larger than Generic. Rule k is less efficient than Generic, so it generates a larger CDS, especially when the network is very dense. (b) is the comparison of the number of forwarding edges. In Rule k and Generic, all the dominating edges of forwarding nodes are their forwarding edges. ECC has a much smaller number of forwarding edges than CDS, especially when n is large. Figures 7 (c) and (d) show the numbers of switched-on sectors in Rule k and Generic (all sectors of each forwarding node are switched-on due to the omnidirectional antenna), and ECC, when K is 4 and 6 respectively.

Figure 8 shows the results of the three algorithms when the original graph is undirected ($r = 40$). (a) shows the selected forwarding nodes, (b) is the forwarding edges, and (c) and (d) are the switched-on sectors when K is 4 and 6, respectively. Compared with Figure 7, a larger transmission range and more links lead to a smaller forwarding node set for all four algorithms. However, Rule k and Generic have larger forwarding edge sets because each forwarding node tends to have more edges. ECC has a smaller forwarding edge set than those in Figure 7. In (c) and (d), Rule k and Generic have smaller switched-on sectors than in Figure 7 due to the reduced number of forwarding nodes. Since the relative performance of the four algorithms is the same as in directed graph, we set the original graph to be directed in the following without loss of generality.

Figure 9 shows the performance ECC with different h values. (a) and (b) show the numbers of forwarding nodes and edges in the DCDS, with 2, 3, and 4 hops local information. We can see that, with more local information, the smaller DCDS can be achieved in terms of both forwarding nodes and edges. However, when h increases from 3 to 4, the performance improvement is not significant. Thus, a relatively small h is appropriate for the localized ECC. In ECC, the increase of h helps to reduce both forwarding nodes and forwarding edges.

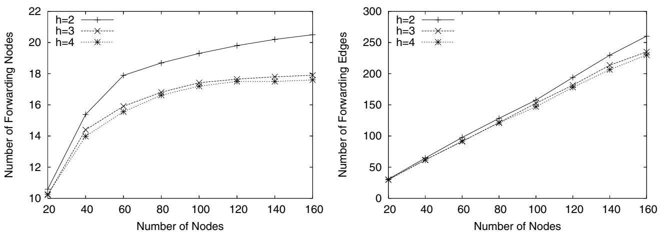
Simulation results can be summarized as: (1) ECC can be applied to both directed and undirected graphs. In undirected graphs where there are more edges, ECC reduces the number of forwarding edges more significantly than that in directed graphs. (2) ECC generates the DCDS with fewer forwarding edges than Rule k and Generic. (3) Using directional antennas, the number of switched-on sectors of ECC is smaller than those of using omnidirectional antennas. (4) More local information helps to improve the performance ECC, but a relatively small h is sufficient.



(a) Forwarding nodes (b) Forwarding edges

(c) Switched-on sectors ($K = 4$) (d) Switched-on sectors ($K = 6$)

Figure 8. Comparison of Rule k, Generic, and ECC in undirected graphs ($r = 40$).



(a) Forwarding nodes (b) Forwarding edges

Figure 9. ECC performance with different h.

6 Conclusions

In this paper, we put forth the concept of a directional network backbone. Using directional antennas, constructing a directional network backbone in MANETs further reduces total energy consumption as well as reducing interference in broadcasting applications. We develop the concept of the directional connected dominating set (DCDS) which is an extreme case of directional backbone. A heuristic localized algorithm for constructing a small DCDS is proposed. The sector optimization algorithm is developed for the second phase. Performance analysis is conducted, including a theoretical analysis in terms of the approximation ratio and a simulation study of the ECC algorithm. Our future work includes some extensions of the ECC algorithm, such as applying ECC to topology control.

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