On Reducing Broadcast Transmission Cost and Redundancy in Ad Hoc Wireless Networks Using Directional Antennas

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***Abstract*—Using directional antennas to conserve bandwidth and energy consumption in ad hoc wireless networks has attracted much attention from the research community in recent years. However, very little research has focused on applying directional antennas to broadcasting. In this paper, we propose a virtual link reduction (VLR)-based broadcasting protocol for ad hoc wireless networks using directional antennas. Based on two-hop neighborhood information, VLR relies on no location nor angle-of-arrival (AOA) information. VLR is a localized or distributed protocol, and it achieves full delivery. VLR operates on top of any existing broadcast routing protocols. In VLR, no node rebroadcasts a given packet more than once. No physical link is actually reduced, but if a packet has already been forwarded to the end node of the current link, the packet is no longer forwarded, that is, this link is virtually reduced. To evaluate the performance of the proposed VLR-based protocol, we conduct extensive simulation, for simplicity, assuming that there is no packet collision, no channel contention, and no mobility. Simulation results show that VLR outperforms most existing omnidirectional and directional broadcasting schemes in the sense that its normalized transmission cost and redundancy are significantly reduced. Based on the results, we conclude that VLR is more bandwidth and energy efficient.**

***Index Terms*—Broadcasting, directional antennas, virtual link reduction, wireless ad hoc networks.**

I. Introduction

USING omnidirectional antennas in wireless ad hoc networks can be highly inefficient in terms of power and capacity because a rather small portion of the transmission power is actually intercepted by the antenna of the intended receiver. The rest of the power spreads in the surrounding space causing unwanted and harmful interference. Different from its omnidirectional counterparts, directional antennas achieve better signal-to-noise ratio and reduce interference by applying directional beams for both transmission and reception. Consequently, transmission and reception of information through directional antennas is significantly desirable. Using smart antennas (i.e., directional antennas) to conserve bandwidth and energy consumption in ad hoc networks has attracted much attention from the research community recently [3], [11]–[13], [20], [23], [25], [29], [30]. However, most of them focused on the medium access control (MAC) layer, and few works consider efficient broadcasting in ad hoc networks using directional antennas.

Network-wide broadcasting (or simply broadcasting for the remainder of this paper) refers to the process in which a source node sends a packet to all other nodes in the network. Wireless ad hoc networks (or simply referred to as ad hoc networks) are wireless nodes that cooperatively form a network without infrastructure or centralized administration. In such networks, nodes act as both hosts and routers, assisting in packet forwarding. Broadcasting is essential in ad hoc networks not only for data dissemination but for route discovery, resource discovery, and management as well. In [27], the authors categorize broadcasting into four families: simple flooding, probability-based methods, area-based methods, and neighbor-knowledge-based methods. In simple flooding (i.e., blind flooding), every node forwards the broadcast packet exactly once. This kind of protocols waste too much network bandwidth, consume too much energy, and have excessive redundancy, which, in turn, causes the broadcast storm problem [26]. Both probability- and area-based methods [26] are designed to solve the aforementioned broadcast storm problem. In such schemes, each node estimates its potential contribution to the overall broadcasting process before forwarding a broadcast packet. The packet is not forwarded if the estimated contribution is lower than a predefined threshold. Although the schemes can solve the broadcast storm problem to some extent, full delivery may not be guaranteed, even in ideal networks. Neighbor-knowledge-based protocols select a small set of forward nodes based on localized topology information to achieve full delivery. Neighbor-knowledge-based schemes are more efficient than probability- and area-based approaches [27]. Nevertheless, their efficiency can further be improved because of the fact that

Manuscript received June 13, 2009; revised August 28, 2009. First published December 8, 2009; current version published March 19, 2010. This work was supported in part by grants from RGC under Contract 615608 and Contract 616207, by a grant from NSFC/RGC under Contract N_HKUST603/07, by a grant from HKUST under Contract RPC06/07.EG27, by NSFC (No. 90612018), and by the China 973 Program (No. 2006CB303000). The review of this paper was coordinated by Prof. Y.-B. Lin.

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Digital Object Identifier 10.1109/TVT.2009.2038167

finding the smallest set of forward nodes with or without global network information to achieve full delivery has been proved to be NP-hard.

On the other hand, the aforementioned broadcasting schemes assume omnidirectional transmission and reception. Hence, the fewer forward nodes there are, the less the redundancy, transmission cost, and bandwidth consumption will be. However, when directional antennas are used, this is not the case. The new challenge is to compute a small collection of directions used in a broadcasting process and, meanwhile, to ensure that full delivery is guaranteed. By doing so, redundancy, transmission cost, bandwidth consumption, and interference can further be reduced. Several protocols, including [1], [2], [10], and [22], have been proposed toward efficient broadcasting using directional antennas. However, most of them are probability-based approaches, rely on location or angle-of-arrival (AoA) information, or assume specific antenna models. In [21], AoA is defined as the angle between the propagation direction of an incident wave and some reference direction, which is known as orientation. The orientations of the unknown nodes may or may not be known at the time of deployment. Furthermore, at least two noncollinear neighbor beacons are required to discover the location when the orientations are known and at least three to discover both the location and the orientation.

In this paper, we propose a virtual link reduction (VLR)-based protocol, which aims to achieve full delivery while significantly reducing the transmission cost, redundancy, and bandwidth consumption by switching off transmission in unnecessary directions. VLR is a localized approach where no location or AoA information is used. During the broadcasting process, each node determines its status and computes the forward directions based on only two-hop neighborhood information (or simply referred to as two-hop information), which is collected via two rounds of "Hello" message exchanges among neighbors. In VLR, no node rebroadcasts a given broadcast packet more than one time, which prevents loops. The data packet is forwarded only in directions with "unreduced links," instead of all directions. Any physical link is not actually reduced, but if a packet has already been forwarded to the end node of the current link, the packet is no longer forwarded. That is, this link is virtually removed. The directional information (i.e., how to form a directional beam to reach a specific neighbor) is piggybacked in the two-hop information, which does not require extra overhead to collect. In VLR, directional beams can be irregular, overlapping, and unaligned, which means that VLR adapts well to a wide scope of antenna techniques.

To evaluate the performance of VLR, we compare against the self-pruning algorithm through simulations. The self-pruning [directional self-pruning (DSP)] [6] outperforms most existing localized broadcasting schemes, both omnidirectional ones and directional ones included, in terms of efficiency, quality, and/or reliability. The simulation results show that, when the transmission area of each node is partitioned into more than four directions, VLR uses about 30% less transmission cost and results in approximately 30% less redundancy compared with DSP. Based on the simulation, we assert that VLR achieves *even much lower* redundancy and is *even more* bandwidth and energy efficient.

The rest of this paper is organized as follows. In Section II, existing broadcasting schemes using omnidirectional or directional antennas are reviewed. Section III describes our antenna model and local topology information maintenance and formulates an efficient broadcasting problem. The VLR algorithm is presented in Section IV, and its properties are also discussed there. Simulation results are presented in Section V, and this paper is concluded in Section VI.

II. Related Work

As mentioned before, there are four main schools of forwarding protocols. Here, we only focus on neighbor-knowledge-based (i.e., localized) deterministic broadcasting approaches using omnidirectional antennas, which are considered to be more efficient than probability- and area-based ones [27]. Most of the localized deterministic broadcasting algorithms aim to form a connected dominating set (CDS). It is well known that finding a minimal CDS with global network information has been proven to be NP-hard. In a localized way, this problem is more challenging. This class of schemes can be further divided into neighbor-designating methods and self-pruning methods. In neighbor-designating methods [16]–[18], the source node selects a subset of its one-hop neighbors as forward nodes to cover its two-hop neighbors. Each forward node, in turn, determines the status (forward or nonforward) of its one-hop neighbors in a similar way. In self-pruning methods [5], [19], [24], [28], each node makes a decision about its own status (forward or nonforward).

There are only a few localized broadcasting schemes using directional antennas in the literature, most of which are probability based, depend on location or AoA information, or assume specific antenna models [1], [2], [10], [22]. Perhaps the most relevant work to VLR is the localized deterministic approach DSP [6], which assumes no location information or AoA information and in which a general antenna model is used. In DSP, for a given forward node, if it determines that, for a given direction, there are no uncovered one-hop neighbors, the forward node will not transmit in that direction. Basically, DSP assumes that two-hop information is available. A node w in node v's local view is covered if and only if 1) w is a known forward node, 2) w is a neighbor of a known forward node u and w is within one of u's forward directions, or 3) w is a neighbor of a covered node with a higher ID than v. In DSP, the direction information (i.e., how to form a directional beam to reach a specific neighbor) is piggybacked in the two-hop information, and forward directions (i.e., the directions a forward node switches on) are piggybacked in the broadcast packet. It is proven that DSP achieves full delivery. Other relevant works to VLR include [14] and [15]. However, VLR differs with them in at least three aspects: 1) Both [14] and [15] make use of location information; 2) they are destined to topology control in ad hoc networks; and 3) they assumed omnidirectional antennas. The key difference between VLR proposed here and DSP is that DSP does not consider link reduction.

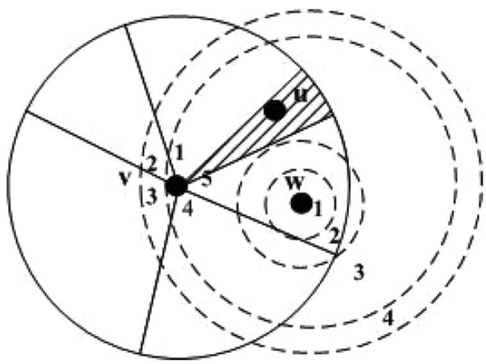

Fig. 1. General directional antenna model.

III. Problem Formulation

In this section, we first introduce our antenna model that is very general and adapts well to a wide range of directional antenna techniques. Then, we describe the local topology information maintenance scheme used in our method, which is designed to collect/exchange two-hop information and the relative directions of neighbors with no help of location or AoA information. Finally, the problem of efficient broadcasting using directional antennas is defined.

A. Antenna Model

In [20], the authors illustrate the techniques used in smart antenna systems to form directional transmission and/or reception beams. Similar to DSP [6], VLR uses a general antenna model that has few constraints, that is, VLR does not rely on a specific antenna pattern. Fig. 1 is an example of this model. Each node can transmit and/or receive in K directions with IDs $1, 2, \ldots, K$. Directional beams do not have to be regular, aligned, or nonoverlapping. In Fig. 1, node v has cone-shaped directional beams, while node w has ringlike directional beams. Node v can reach node u in direction 1 or 5, which is shown by the shadowed area. We also notice that node u can be reached by w in direction 3 or 4. The only constraint is that each directional beam is predefined in terms of its size and shape. There are two reception modes: the omnidirectional mode, where a node can receive from all neighbors, and the directional mode, where a node receives from neighbors in a single direction. Throughout this paper, we assume an omnidirectional reception mode and a directional transmission mode, although this is not a must.

Next, we introduce our mathematical notation under a general directional antenna model.

For each node v, $N_i(v)$ denotes the set of nodes within the transmission and reception range of v's ith direction, and $N(v) = N_1(v) \bigcup N_2(v) \bigcup \ldots \bigcup N_K(v)$ is v's one-hop neighbor set. A neighbor may appear in several directions if overlapping directions are allowed. $D_{v\to u} = \{i | u \in N_i(v)\}$ indicates the set of v's directions, and in each of them, v can reach u. In Fig. 1, $N(v) = \{u, w\}$, where u, $w \in N_5(v)$, and $u \in N_1(v)$. Therefore, $D_{v\to u} = \{1, 5\}$ and $D_{v\to w} = \{5\}$. The ad hoc network is assumed to be symmetric and connected via bidirectional links, which means that if u can reach v by one hop, v can also reach u by one hop. Consequently, the ad hoc network is viewed as a graph $G = (V, E)$, where V is the set of wireless nodes, and E is the collection of bidirectional links. A wireless link $(u, v) \in E$ if and only if $v \in N(u)$ and $u \in N(v)$.

B. Local Topology Information Maintenance

Using directional antennas, upon receiving a packet, each node must decide whether this packet should be forwarded, where to forward it, and which directional beam to use. To make a better decision, neighborhood information must be exchanged among neighbors (one- or two-hop neighbors). In this section, we will describe an information exchange algorithm (a similar scheme was first proposed in [6]). Each node sends periodical "Hello" messages to its neighbors. Each "Hello" message is piggybacked with the sender v's ID, direction ID, $N(v)$, and $D_{w\to v} : \forall w \in N(v)$. At first, $N(v)$ and $D_{w\to v} : \forall w \in N(v)$ are empty. By collecting "Hello" messages from its neighbors for the first time, v obtains information about its one-hop neighbors, together with directions in which those neighbors reach v. However, at that time, v still has no idea about the directions used to reach a neighbor u. In the following intervals, by exchanging one-hop information $N(v)$ and $D_{w\to v} : \forall w \in N(v)$ of each node v, two-hop information $N^2(v)$ is constructed. Specifically, $N^2(v)$ carries the following information: 1) for any two nodes u and w in $N(v) \bigcup v$, whether there exists a link (u, w); 2) if such a link exists, the set of directions $D_{u\to w}(D_{w\to u})$ that node $u(w)$ uses to reach node $w(u)$; and 3) for any two nodes u and w such that $u \in N(v)$ and w is a two-hop neighbor of v, whether there exists a link (u, w). Special attention should be paid to term 3 in the sense that although how one-hop neighbors reach two-hop neighbors is not known, due to the assumption that the network is symmetric, a link between a one-hop neighbor u and a two-hop neighbor w exists if the directions used by w to reach u are known. In the aforementioned scheme, each "Hello" message is sent out in each of the K directions by each node.

Notes:

1) One may argue that such a scheme can incur extra overhead. However, given the same neighborhood area, the bandwidth and energy consumption of each directional transmission is roughly $1/K$ that of an omnidirectional transmission if a sector antenna is used. Therefore, the total cost of our scheme is very similar to that of using omnidirectional "Hello" messages.
2) Even though k-hop, with $k > 2$, information can help make a better forwarding decision, k-hop, with $k > 2$, information exchange may cause slower convergence and is more vulnerable to node movement. The gain in performance improvements may not be worthwhile considering the complexity of using more-hop information. Therefore, in this paper, we limit up to two-hop information exchange.
3) The local topology information is up to date if node movement is relatively slow with respect to the predefined "Hello" interval. Otherwise, no localized approach based on local topology information is reliable.

4) Similar to [6], it is assumed that there is no packet collision (an ideal MAC layer); otherwise, full delivery cannot be achieved even under blind flooding.

C. *Efficient Broadcasting Problem*

Traditionally, omnidirectional-antenna-based broadcasting protocols aim to find the smallest set of forward nodes to achieve low redundancy, low energy consumption, and/or low interference and contention, while full delivery should be guaranteed. However, for directional-antenna-based broadcasting approaches, special consideration must be taken into account. More efficient forwarding can be achieved only by selecting the smallest set of directions involved in the broadcasting process.

To facilitate the description of the problem formulation, we define a forward scheme F as a function of V, where $F(v)$ is the set of v's forward directions. Given a source node s and a forward scheme F, we say that a node d is *reachable* from s (i.e., $s \Rightarrow d$) if and only if $s = d$ or there exists a forward path $P : (v_1 = s, v_2, \ldots, v_i = d)$ satisfying that every node in P forwards in the direction toward its successor.

To assess the cost associated with the forwarding in each direction, let $A(i)$ be the angle or beamwidth of direction i. For each forwarding direction i, the cost incurred is $c + A(i)$, where c is a constant cost for opening any direction, regardless of the beamwidth. That is, for each direction, there is a fixed cost, as well as the cost associated with the beamwidth $A(i)$. If the antenna has fixed K directions, then $A(i) = 360/\mathrm{K}$.

For a given antenna model, a forward scheme F, and a source node s, we define the transmission cost of the forward scheme as

$$|F| = \sum_{v\in V}\sum_{i} \left(c + A(i)\right) N(i,v))$$
$$= \sum_{v\in V}\sum_{i} \left(A(i)N(i,v)\right) + c\,|F(v)|)$$

where $N(i,v)$ is the number of forwarding directions using angle i by node v. If the antenna has K equal-angle directions, the angle of each direction is 360/K, and $c = 0$, the cost function $|F| = \sum_{v\in V} |F(v)|$, noting that $|F(v)| = \sum_i N(i,v)$ and that $A(i) = 360/K$. Now, we can formulate the efficient broadcasting problem using directional antennas as follows.

Extended Efficient Broadcasting Problem: To assess the cost associated with the forwarding in each direction, let $A(i)$ be the cost associated with the angle or beamwidth of direction i. For each forwarding direction i, the cost incurred is $c + A(i)$, where c is a constant cost for any direction, regardless of the width of the beam. That is, for each direction, there is a fixed cost c, and there is the cost associated with the beamwidth $A(i)$. For example, the fixed cost of c could include the common power used by all the electrical parts associated with the antenna, the power required for switching from one direction to another, and the cost associated with instability when the beam becomes very narrow, just to name a few, and its value depends on the specific antenna to be used.

IV. Virtual Link Reduction Forwarding

In this section, we propose an efficient forwarding scheme. To this end, we first introduce the concept of link weight, which is an important metric in our forwarding scheme design. Then, we present the VLR-based broadcasting scheme using directional antennas (VLR). Finally, we prove that our VLR achieves full delivery.

A. *Definition*

Traditionally, Euclidean distance is used to identify the weight of a link in most wireless applications. However, to get an accurate estimation about the distance between nodes, special devices such as Global Positioning System receivers are needed. The required location devices would cause extra overhead and cost. In addition, the existence of side lobes of antenna beams may also cause problems. In this paper, we assume that every node v has a unique ID denoted as $ID(v)$. Therefore, an appropriate definition about the link weight should be given as follows.

Link Weight: Given a network $G = (V, E)$, we say that (u_1, v_1) has a lower weight than (u_2, v_2) [i.e., $(u_1, v_1) < (u_2, v_2)$], where $u_1, v_1, u_2, v_2 \in V$, and $(u_1, v_1), (u_2, v_2) \in E$ if and only if 1) $\min(ID(u_1),\ id(v_1)) < \min(ID(u_2),\ ID(v_2))$ or 2) $\min(ID(u_1), ID(v_1)) = \min(ID(u_2), ID(v_2))$ and $\max(ID(u_1), id(v_1)) < \max(id(u_2), id(v_2))$.

Note that, here, the reason we use IDs is that the definition we use makes each link's weight unique since each node's ID is unique. Furthermore, we use the weight defined earlier to find a minimum spanning tree (MST). Other weights such as the energy level on both nodes of the link or the cost can be used.

B. *VLR-Based Broadcasting*

In our scheme, each forward node v piggybacks its forward direction information $F(v)$ in the broadcast packets.

Algorithm 1: VLR Rule at Each Node v

1) Based on the two-hop neighborhood information (i.e., $N^2(v)$), a node v computes the localized broadcasting tree $T_v = (V(N^2(v)), E(T_v))$ by applying Prim's algorithm.
2) Link e is reduced if $\{e\} \bigcap E(T_v) = \emptyset$.
3) Link $e = (v, w)$ is reduced if $e \in E(T_v)$ and if w is a neighbor of a known forward node u and is within one of u's forward directions (i.e., $D_{u\to w} \bigcap F(u) \neq \emptyset$).
4) Link $e = (v, w)$ is reduced if $e \in E(T_v)$ and if w is the parent of v (i.e., the first coming broadcast packet is from w).
5) Return the reduced link set $L_v(\text{Unreduced}) = \{(v, w) | w \in N(v) \bigwedge \text{Reduced}(v, w) = \text{false}\}$.

Algorithm 2: VLR-Based Broadcasting (VLR at Each Node v)

Upon receiving a broadcast packet (source node included), if it is received for the first time, the VLR rule is exploited

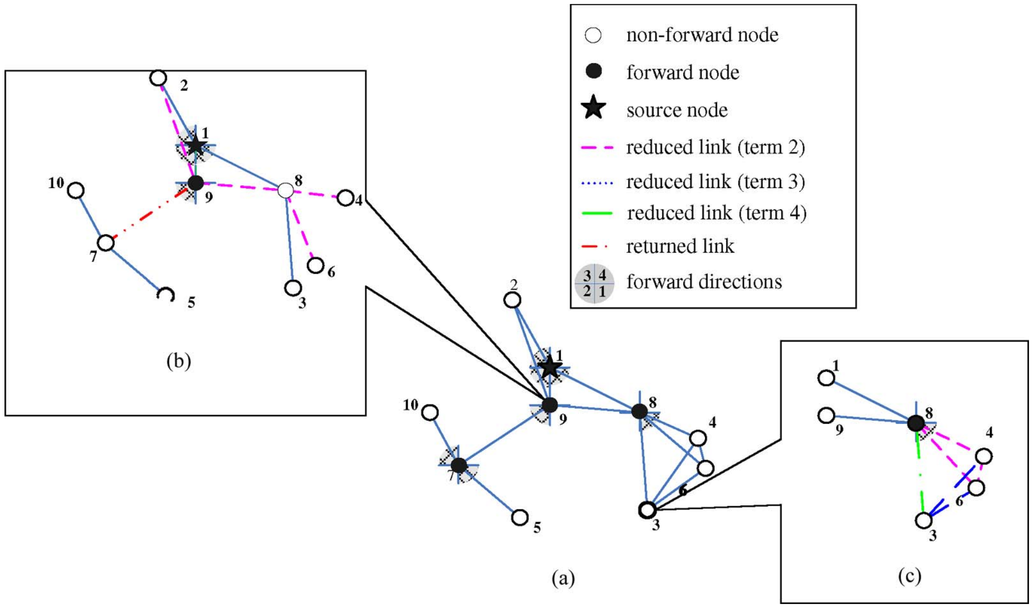

Fig. 2. VLR used in a network with ten nodes. Each node with an ideal four-sector directional antenna. (a) Efficient broadcasting. (b) Node 9's local view. (c) Node 3's local view.

to compute the forward directions; otherwise, it is dropped by v:

1) Compute the reduced link set $L_v(\text{Unreduced})$ based on the VLR rule.
2) If $L_v(\text{Unreduced}) = \emptyset$, the broadcast packet is dropped (i.e., $F(v) = \emptyset$).
3) Otherwise, v becomes a forward node, and $F(v) = \{d_{v\to w} | (v, w) \in L_v(\text{Unreduced})\}$.

In VLR, no node rebroadcasts a given broadcast packet more than one time, which prevents infinite loops. The data packet is transmitted only in directions with unreduced links, instead of all directions. That is, any physical link is not actually reduced, but if a packet has already been forwarded to the end node of the current link, the packet is no longer forwarded. That is, this link is virtually removed. This is the core of VLR and is different from many existing forwarding schemes.

For each unreduced link $(v, w) \in L_v(\text{Unreduced})$, at least one direction $d_{v\to w} \in D_{v\to w}$ is selected as a forward direction in $F(v)$. Once the direction is selected, one can adjust the beamwidth so that the beamwidth is as small as possible while still covering the node, using Algorithm 3.

Algorithm 3: Adjust Angle of the Directional Antenna

1) Reduce the angle of one directional antenna by m degrees. The new angle of the antenna should not be smaller than a predefined threshold $(minimal\_angle)$.
2) After the angle reduction, compare the number of nodes covered by the new angle with that by the old angle. If the new number is the same as the old number, go to step 1. If the new number is smaller than the old number, use the old angle, and go to step 3.
3) Return the modified angle of the directional antenna.

In the case in which an unreduced link may be covered by different directions (i.e., $|D_{v\to w} > 1|$), a greedy heuristic algorithm in [7] can be applied to select a minimum $F(v)$ that covers all links in $L_v(\text{Unreduced})$. Note that, since each node's ID is globally unique and, subsequently, each link's weight is globally unique according to our definition of the link weight, our VLR is deterministic and predictable, given the source s, antenna model, and network topology. The time complexity of Prim's algorithm is $O(n \log n + e \log n) = O(e \log n)$, where n is the number of nodes, and e is the number of edges. This can be improved using *Fibonacci heaps* to $O(e + logn)$ [9].

Fig. 2 is an example of VLR, where a total of seven forward directions are used. Source node 1 transmits in directions 1, 2, and 3, because in its local view, $L_1(\text{Unreduced}) = \{(1, 2), (1, 8), (1, 9)\}$. Node 9 transmits in direction 2, in that, in its local view [as shown in Fig. 2(b)], $L_9(\text{Unreduced}) = \{(7, 9)\}$. In node 7's local view, $L_7(\text{Unreduced}) = \{(5, 7), (7, 10)\}$; therefore, it transmits in directions 1 and 3. Similarly, node 8 transmits in direction 1, since in its local view $L_8(\text{Unreduced}) = \{(3, 8)\}$. Special attention should be paid to Fig. 2(c), in which node 3 drops the broadcast packet since $L_3(\text{Unreduced}) = \emptyset$ in its local view, or all the links emitting from node 3 are virtually reduced.

To further conserve energy, once a forward direction is selected, one should adjust the beamwidth so that the angle is as small as possible while still covering the node. Since we do not know the location of neighbor nodes, we need to repeatedly reduce the angle, by a small degree, of one node's antenna to assure that the nodes covered by original angle are still covered by the modified angle. If some nodes covered by angle θ_1 before modification are not covered by the new angle θ_2, where $\theta_2 = \theta_1 - m$, the angle of the antenna will not be modified, that is, the angle of the antenna will be the value of the last modification θ_1. The smaller m is, the smaller the modified antenna's angles that we get. The following is an angle-adjust algorithm in which m is the value to which we reduce the angle of an antenna at one time.

C. Properties of VLR

In this section, we prove that VLR guarantees full delivery.

Theorem 1: The forward scheme determined by VLR achieves full delivery.

Proof: Here, we prove that the induced directed graph $G(\mathrm{VLR}) = (V(G), E(\mathrm{VLR}))$ is connected. First, we prove that undirected $G(\mathrm{VLR})^-$ is connected. We say that $e = (u, v) \in E(G(\mathrm{VLR})^-)$ if e is not reduced by u nor by v (regardless of terms 3 and 4 of the VLR rule). Applying Prim's algorithm to the original entire graph $G = (V, E)$, we get $T_{\mathrm{prim}}(G)$. Clearly, T_{prim} is connected and unique and has $|V| - 1$ links. Assume that there exists a link $e = (u, v) \in E(T_{\mathrm{prim}})$, but $\{e\} \bigcap E(G(\mathrm{VLR})^-) = \emptyset$. In this case, e is reduced by u in u's local view or by v in v's local view. Assume that e is reduced by u in u's local view. There must exist a path $p : (u = w_0, w_1, w_2, \ldots, w_i = v)$ in u's local view where $(w_i, w_{i+1})\langle(u, v), i\rangle = 0$. Then, we can get another $T'_{\mathrm{prim}}(G)$, which is a contradiction to the fact that T_{prim} is unique. Hence, for any $e \in E(T_{\mathrm{prim}})$, we assert that $e \in E(G(\mathrm{VLR})^-)$, which means that $T_{\mathrm{prim}}(G) \subseteq G(\mathrm{VLR})^-$. Clearly, $G(\mathrm{VLR})^- \subseteq G(\mathrm{VLR})$. Consequently, we have $T_{\mathrm{prim}}(G) \subseteq G(\mathrm{VLR})$. Since T_{prim} is connected, $G(\mathrm{VLR})$ is connected. The full delivery is guaranteed. Note that terms 3 and 4 of the VLR rule have no impact on the connectivity of $G(\mathrm{VLR})$.

DSP [6] and VLR are both dynamic and source-dependent broadcasting schemes, where the forward scheme F is determined during the broadcasting process, and using F, two different source nodes may produce different forward schemes.

V. Simulation and Evaluation

A. Protocol in Comparison

In this paper, we compare our protocol with DSP [28], in which the node's ID is used to uniquely identify every node. In one node v's view, its neighbor node w is considered to be covered if at least one of the following conditions are met.

1) The node is already a forward node.
2) The node is covered by a forward direction of a forwarder.
3) The node is a neighbor of a covered node with a higher ID than node v's ID.

If w fails to meet at least one conditions, node v needs to forward a message through its directional antenna that covers node w, or v does not need to forward a message to w since w has already gotten the message from other nodes.

We also compare our protocols with omnidirectional self-pruning (OSP) [6], in which the node's ID is used to uniquely identify every node. In one node v's view, its neighbor node w is considered to be covered if at least one of the following conditions are met.

1) The node is already a forwarder.
2) The node is already covered by a forwarder.
3) The node is a neighbor of a covered node with a higher ID than node v's ID.

If w fails to meet at least one condition, node v needs to forward a message to w, which means that v needs to forward the message in a 360° angle to cover w, or v will not be selected as a forwarder.

The difference between DSP and VLR is that they reduce the forwarding directions from different aspects: DSP focus on how to reduce the neighbor nodes needed to be covered to reduce the forwarding directions based on the node's ID, while our VLR aims to reduce the links based on the MST to reduce the forwarding directions.

B. Simulation in Ideal Networks

The simulation is conducted based on a customized simulator *ds* [4], which simulates several broadcast algorithms including VLR, DSP, OSP [28], and the simple flooding algorithm on random ad hoc networks with 30–160 nodes deployed in a 1000×1000 m area. Unlike *ns-2* [8], where the entire network protocol stack is taken into account, *ds* considers only functions in the network layer, assuming an ideal MAC layer without contention, collision, or node mobility. All nodes have a transmission range of 250 m and an ideal K-sector antenna pattern, where $4 \leq K \leq 360$. Our simulations focus on the following metrics:

1) transmission cost $|F|$;
2) redundancy ratio.

The transmission cost is defined in Section III, and the redundancy ratio is defined as the average number of redundant receptions per node, that is (the redundancy ratio is equal to the total number copies of a packet received by all nodes—the total number of nodes in the network), the total number of nodes in the network. The first metric is a measure of the efficiency of the broadcasting protocol, while the second metric indicates to what extent the protocol deals with the so-called broadcast storm problem [26]. Every simulation is repeated until the 90% confidence intervals of all average results are within $\pm 1\%$.

1) Efficiency: As mentioned before, DSP has been shown to be more efficient than most existing broadcasting protocols [6]. To see how good VLR performs compared with DSP, in Fig. 3(a), we plot the transmission cost of VLR and that of DSP, assuming that $c = 0$ and $A(i) = 1/K$. The cost function under this assumption reduces to a normalized transmission cost. The reason why the bigger the K is, the bigger the cost becomes is that a bigger angle of a directional antenna can cover more nodes, but it also covers much more blank space. For example, two nodes can be covered by one antenna when $K = 4$, but they also can be covered by two antennas when $K = 32$; therefore, if we use $k = 32$, we use less cost to cover two nodes that can be covered by one antenna of $K = 4$. From the figure, we notice that the transmission cost under VLR with $K = 8$, 16, 32, and 360 is about 30% less than that of DSP, particularly when the network is dense. VLR (with $K = 4$) uses slightly more forward directions than DSP in dense networks. The results indicate that VLR performs much better than DSP in most cases.

OSP has been shown to outperform most omnidirectional broadcasting protocols in terms of efficiency. Again, assuming that $c = 0$ and $A(i) = 1/K$, we would like to see how good VLR performs compared with OSP and the blind flooding

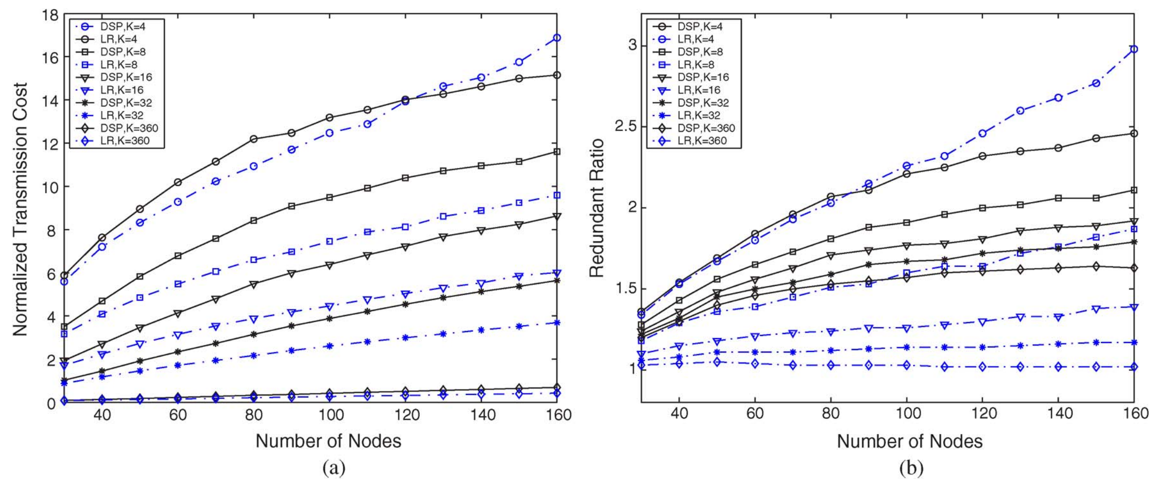

Fig. 3. Simulation results in ideal networks (VLR versus DSP). (a) Normalized transmission cost. (b) Redundancy ratio.

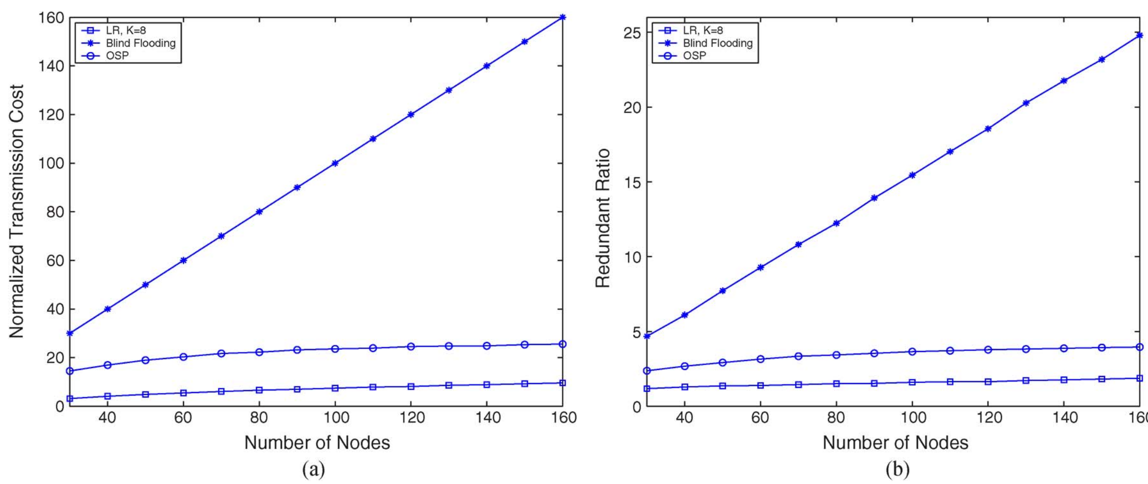

Fig. 4. Simulation results in ideal networks (VLR, OSP, and blind flooding). (a) Normalized transmission cost. (b) Redundancy ratio.

protocols. In Fig. 4(a), we compare the performance of VLR, OSP [28], and blind flooding in terms of normalized transmission cost. We note that VLR significantly outperforms the other two protocols.

When there is a fixed cost associated with each forward direction, it is not necessarily true that the smaller the antenna angle (or the big the K), the better the transmission cost. To study of the impact of the fixed cost c on the VLR performance, we conduct simulations for various values of c and for different network sizes. It is expected that, as c increases, the number of forwarding directions or sectors K should decrease.

In Figs. 5(a) and (b) and 6(a), we compare the transmission cost for different values of c for a network with 100, 80, and 60 nodes, respectively. From the figures, the impact of c is obvious, and the optimal value of K (sectors) decreases as the value of fixed cost c increases. This states that there is a tradeoff between the transmission cost and the number of sectors. As mentioned before, we use more antennas of small angle to cover the same number of neighbor nodes that can be covered by fewer antennas of bigger angle. However, on the other hand, since opening an antenna will have a fixed cost c, the more antennas we need, the more fixed cost will be needed. Therefore, finding a balance between K and c is very important, which has been shown in Figs. 5(a) and (b) and 6(a).

In Fig. 6(b), the sector number is assumed to be 8, the number of nodes is 100, and the transmission range is 250 m. Under these assumptions, we compare the redundancy with different area sizes ranging from 500 m $*$ 500 m to 2000 m $*$ 2000 m. As the area increases, the redundancy decreases. We can use an example to show how this happens. For example, when the density is high, then node A is very close to node B. A and B are neighbors of node D, and A has already been covered by node C, but B is not, so in D's view, it does not need forward to A, but it should forward to B. Therefore, D will open an antenna that can cover B; unfortunately, this antenna will cover A again. As a result, A will receive two replicas of one message. However, it will seldom happen when the density is low because it is very possible that A and B are so distant from each other that one of D's antenna can cover A and B at the same time. This explains why the redundancy is small when the density is low.

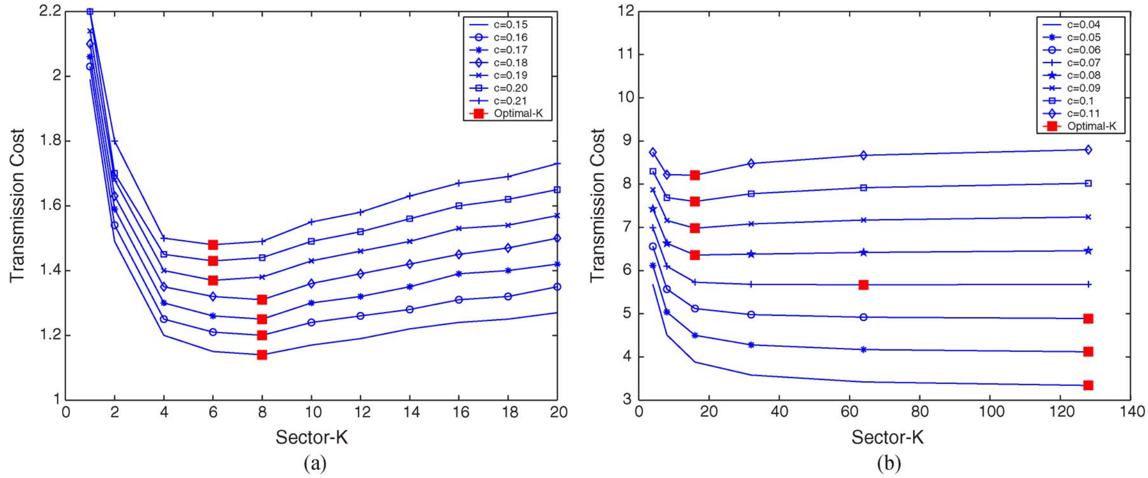

Fig. 5. Transmission cost versus number of sectors. (a) One hundred nodes. (b) 80 nodes.

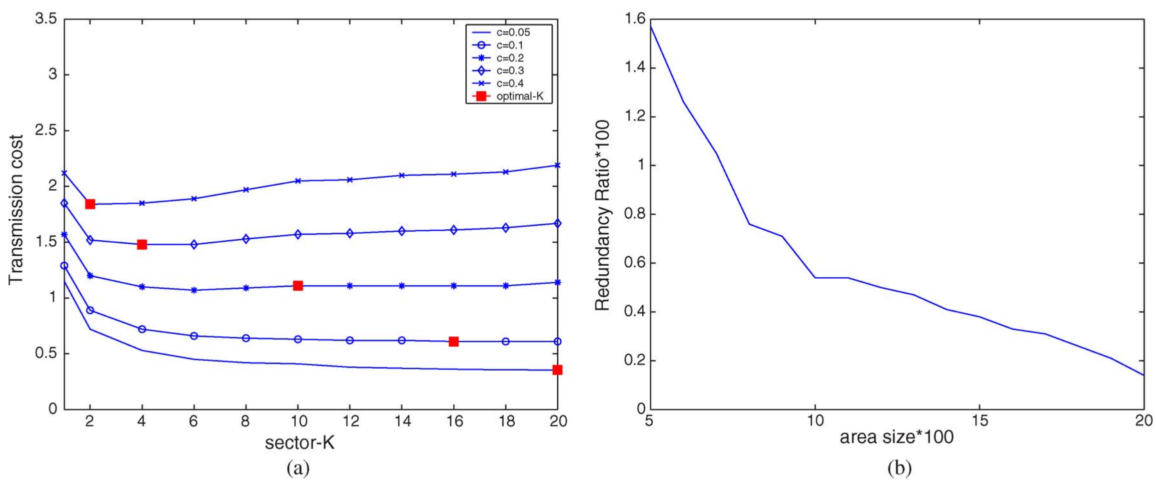

Fig. 6. Transmission cost and redundancy ratios. (a) Sixty nodes. (b) Redundancy ratio versus size of the area.

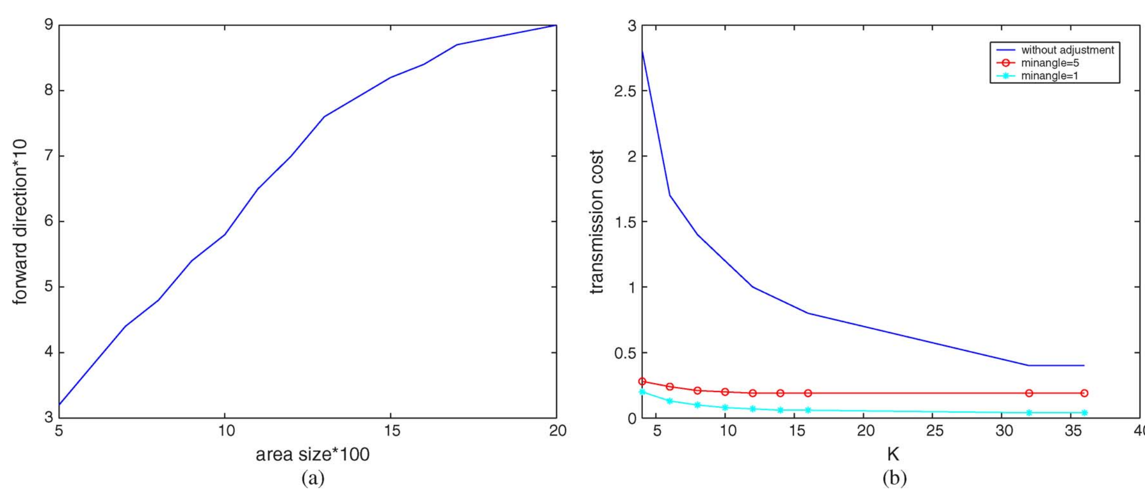

Fig. 7. Simulation results on the number of forward directions and transmission cost with adjustment. (a) Forward 100. (b) Adjustment.

In Fig. 7(a), the number of sectors is kept at 8, the number of nodes is kept at 100, and the transmission range is kept at 250 m. Under these assumptions, we compare the number of forward directions with different area sizes ranging from 500 $*$ 500 m to 2000 $*$ 2000 m.

When the beamwidth is adjustable, applying the angle adjustment algorithm, we can further reduce the energy consumed. To see how much energy can be saved compared with that without applying the angle adjust algorithm, we conduct simulation for different values of sectors K and for different thresholds on the minimal angle one can use. We assume that the area size is $1000 * 1000$ m and that the number of nodes is 40. In Fig. 7(b), we plot the transmission cost versus the number of sectors K for different values of the minimal angles. From the figure, we notice that, applying angle adjustment, the transmission cost is significantly reduced compared with that without adjustment, particularly when the number of sectors is small. This is expected as when the number of sectors is small, the angle required to cover all the area is larger. If there are only a few nodes in the forwarding direction and if they can be covered by a small angle, applying the angle adjustment, a significant amount of energy can be saved. It is noted that the threshold of the minimal angle one can adjust also has impact on the transmission cost.

2) Redundancy Ratio: To study how much redundancy VLR introduces, in the simulation, we collect statistics related to the redundancy ratio define earlier and compared it with that under DSP, OSP, and blind flooding protocols.

In Fig. 3(b), we compare the redundancy of VLR and that of DSP. The redundancy ratios of VLR are only about 60%–70% of those of DSP ($K = 8$, 16, 32, 360). In particular, the redundancy ratios of VLR remain almost unchanged as the number of nodes increases. This illustrates the advantage of VLR. VLR (with $K = 4$) performs a little worse than DSP (with $K = 4$), particularly when the network is dense. In Fig. 4(b), we show that VLR significantly outperforms OSP and simple flooding in terms of redundancy.

VI. Conclusion

In this paper, we have proposed a novel and efficient broadcasting algorithm (VLR) in ad hoc networks using directional antennas. VLR is a localized, dynamic, source-dependent, and deterministic approach. Compared with DSP, which outperforms most existing broadcasting protocols in terms of efficiency, quality, and/or reliability, VLR achieves much lower redundancy and transmission cost and consequently conserves bandwidth and energy consumption. Similar to DSP, VLR assumes neither location nor AoA information. Furthermore, ideally, VLR achieves full delivery.

As for future work, we plan to make a mathematical analysis to see whether the number of forward directions of VLR is within a constant factor of an optimal one. In addition, simulations on realistic networks where there exist channel contention, packet loss, and node mobility are on the way.

Acknowledgment

The authors would like to thank Dr. J. Wu for his treasured advice on this paper.

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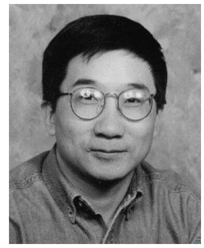

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