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### Authors
Garcia-Luna-Aceves, J.J.
Spohn, M.A.



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# Improving Broadcast Operations in Ad Hoc Networks Using Two-Hop Connected Dominating Sets


Marco Aurélio Spohn
Computer Science Department
University of California at Santa Cruz
Santa Cruz, CA 95064
maspohn@cse.ucsc.edu

J.J. Garcia-Luna-Aceves
Computer Engineering Department
University of California at Santa Cruz
Santa Cruz, CA 95064
jj@cse.ucsc.edu


## I. Introduction

We introduce the *three-hop horizon pruning* (THP) algorithm to make broadcast operations more efficient in ad hoc networks using contention-based MAC protocols. THP builds a *two-hop connected dominating set* (TCDS) of the network, which is a set of nodes such that every node in the network is within *two* hops from some node in the dominating set. Efficiency of broadcast operations is attained by implementing forwarding schemes that take advantage of a TCDS. More specifically, every node provides its one-hop neighbors with a list specifying one or more tuples, each with the identifier of a one-hop neighbor and a bit indicating if that neighbor dominates *any* two-hop neighbor. To forward a broadcast packet, a node tries to obtain the smallest subset of *forwarders*, which are one-hop neighbors that use some of the node's two-hop neighbors to reach *any* node that is three hops away. After such a selection of forwarders, the node broadcasts its packet with a header specifying the list of forwarders, and each forwarder in turn repeats the process.

THP is the first heuristic to take into account three-hop information in the selection of relay nodes for broadcast packets, while incurring signaling overhead that is much the same as that of heuristics based on two-hop information. THP is also the first neighbor-designated algorithm for computing TCDS. The one-hop neighbor list and the *one-hop dominating list* communicated to a node by its one-hop neighbors provide the node with a three-hop horizon of how a broadcast message can be propagated to nodes that are three hops away, even though they are unknown.

When a neighbor-information-based broadcast protocol is used, because every node has the two-hop neighborhood information, it is possible to maintain fresh routes to all nodes within two hops . For example, in on demand routing protocols (e.g., AODV[1]) it is not necessary to broadcast the *route request* (RREQ) packet to every node in the network: disseminating it to a TCDS of the network is enough.


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TABLE I
NOTATION

| | |
|---|---|
| $N_1^i$, $N_2^i$ | One-hop and two-hop neighbors of node $n_i$ |
| $D^j_{\text{1-hop}}$ | *one-hop dominating nodes* of node $n_j$ (computed via DP). That is, $D^j_{\text{1-hop}} \subset N_1^j$ such that $(\bigcup_{k \in D^j_{\text{1-hop}}} N_1^k) = N_2^j$ |
| $\mathcal{F}_i$ | THP forwarder list |
| $\mathcal{C}$ | List of candidates to be forwarders |
| $\mathcal{U}[j]$ | List of *one-hop dominating nodes* of node $n_j$ (i.e., $\mathcal{U}[j] \subset D^j_{\text{1-hop}}$) that need to be covered |

## II. Three-Hop Horizon Pruning

In *Dominant Pruning* (DP) [2], the forwarder list is a set of one-hop nodes such that all two-hop nodes are covered. The approach we use in the Three-Hop Horizon Pruning (THP) algorithm is to make the pruning process in DP more efficient by using topology information three hops away from a given node, but incurring very limited additional signaling overhead in conveying such information.

Let us assume that nodes use HELLO messages to advertise the one-hop neighbor lists of nodes. In addition to informing its one-hop neighbors about its one-hop neighbor list, node $n_j$ also communicates its *one-hop dominating list* $D^j_{\text{1-hop}}$ (computed via DP) to its one-hop neighbors. To reduce the space required for this additional information, the *one-hop dominating list* is encoded in a bit-map format. Because a node lists all its one-hop neighbors in its HELLO message, and because the *one-hop dominating list* is a subset of the one-hop nodes (i.e., $D^j_{\text{1-hop}} \subset N_1^j$), it suffices to signal (i.e., 1 bit per node) which neighbors are one-hop dominating nodes.

The one-hop neighbor list and the *one-hop dominating list* communicated to a node by its one-hop neighbors provide the node with a three-hop horizon of how a broadcast message can be propagated to nodes that are three hops away, even though they are unknown. For node $n_i$, the set of all $D^j_{\text{1-hop}}$ for all $n_j \in N_1^i$, contain the set of two-hop nodes covering all three-hop nodes of node $n_i$.

Instead of simply using the two-hop neighbor coverage as the main criteria for selecting forwarders as is done in standard

**Algorithm 1:** THP

**Data** : $n_i$, $S$ (sender), $D^k_{\text{1-hop}}$ for all $k \in N^i_1$

**Result** : $\mathcal{F}_i$, the forwarder list

**begin**

1 $\mathcal{C} \longleftarrow N^i_1 - N^S_1$

/* Select neighbors with *one-hop dominating nodes* other than one-hop neighbors and the node itself */

2 **for** $n_k \in \mathcal{C}$ **do**

3 $\mathcal{U}[k] \longleftarrow \emptyset$

4 **for** $n_l \in D^k_{\text{1-hop}}$ **do**

5 **if** $n_l \notin (N^i_1 + n_i)$ **then**

6 $\mathcal{U}[k] \longleftarrow \mathcal{U}[k] + \{n_l\}$

/* Exclude candidates covered by another candidate in C */

7 **for** $n_k \in \mathcal{C}$ **do**

8 **for** $n_m \in \mathcal{U}[k]$ **do**

9 **if** $\exists\,(n_l \neq n_k) \in \mathcal{C} \mid n_m \in N^l_1$ **then**

10 $\mathcal{U}[k] \longleftarrow \mathcal{U}[k] - n_m$

11 **if** $\mathcal{U}[k] == \emptyset$ **then**

12 $\mathcal{C} \longleftarrow \mathcal{C} - n_k$

/* For every node $n_k \in \mathcal{C}$, and for every $n_m \in \mathcal{U}[k]$, there is no other $n_l \in \mathcal{C}$ such that $n_m \in \mathcal{U}[l]$; therefore, all nodes in $\mathcal{C}$ are forwarders. */

13 $\mathcal{F}_i \longleftarrow C$

14 **return** $\mathcal{F}_i$

**end**

DP, THP uses the advertised neighbor's *one-hop dominating list* (i.e., $D_{\text{1-hop}}$) to compute which one-hop neighbors have forwarders other than nodes in $N^i_1 + n_i$ (i.e., nodes other than the node itself and its one-hop neighbors). Algorithm 1 presents the pseudo-code for THP (see notation on Table I). Let $\mathcal{C}$ be the list of nodes to be considered as candidates for forwarders. One-hop neighbors of the sender $S$, do not need to be taken into account (line 1), because the sender already did it. For all candidates to forwarders $n_k \in \mathcal{C}$, the list of nodes to be covered (i.e., set $\mathcal{U}[k]$) is built. From the list $D^k_{\text{1-hop}}$, only nodes that are not one-hop neighbors of the current node, $n_i$, and are not node $n_i$ itself, are included in the list $\mathcal{U}[k]$ (lines 2 through 6). The set to be covered, $\mathcal{U}$, is composed of all subsets $\mathcal{U}[k]$ for all nodes $n_k \in \mathcal{C}$. Nodes in $\mathcal{U}[k]$ that are covered (i.e., in another subset of $\mathcal{U}$ or a neighbor of some node in $\mathcal{C}$) by another node in $\mathcal{C}$ can be eliminated (lines 7 through 12). For all candidates $n_k \in \mathcal{C}$, we check for every node $n_m \in \mathcal{U}[k]$ if there is another candidate to forwarder $n_l \in \mathcal{C}$ such that node $n_m$ is a neighbor of node $n_l$. If this is the case, then node $n_m$ can be removed from the set covered by node $n_k$ (i.e., $\mathcal{U}[k]$). If the set $\mathcal{U}[k]$ becomes empty, then node $n_k$ is no longer a candidate to forwarder, and can be removed from the set $\mathcal{C}$ (lines 11 and 12). One restriction when eliminating redundancy from the set $\mathcal{U}$, is that a node $n_k$ must have all its nodes in the set $\mathcal{U}[k]$ checked before proceeding to the next node in the set $\mathcal{C}$. After all nodes in $\mathcal{C}$ are processed, the nodes remaining in the set $\mathcal{C}$ are selected as forwarders.

Figure 1 depicts an example of applying THP, having node $a$ as the source. Every node in the network is within distance two from a forwarder (i.e., dominating node). Because all nodes have information about the two-hop neighborhood, a *route request* (RREQ) message can be disseminated through a TCDS of the network without any loss to the route discovery process. In the worst case, the RREQ will reach a forwarder that is two-hops distant from the destination.

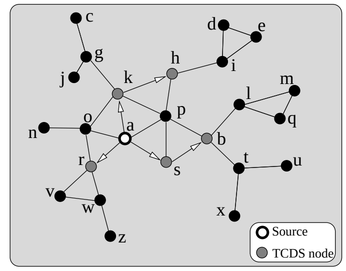


Fig. 1. Using THP to build a TCDS (every node in the network is at most two hops away from a forwarder).

**Theorem 1** *Given a connected graph $G(V, E)$, the node subset $N'$, computed using the THP algorithm, forms a TCDS of $G$.*

*Proof:* By the definition of *one-hop dominating set*, for any node $n_k$ in the network, the set $D^k_{\text{1-hop}}$ is a subset of nodes of $N^k_1$ such that all nodes in $N^k_2$ are covered. First, we consider the set of forwarders defined by the source, $n_i$, and then from the initial set of forwarders, $\mathcal{F}_i$, we show how the TCDS is constructed. For the source node $n_i$, the list of candidates to forwarders, $\mathcal{C}$, include all the one-hop neighbors of node $n_i$ (i.e., $N^i_1$). Because $n_i$ is the source, $S = \emptyset$. The set $\mathcal{U} = \sum_{j \in N^i_1} \mathcal{U}[j]$ cover all three-hop nodes of node $n_i$, because it includes all the nodes covering the two-hop neighborhood of all neighbors of node $n_i$ (i.e., $\forall\, n_j \in N^i_1$, node $n_i$ knows $D^j_{\text{1-hop}}$). A node $n_k \in \mathcal{U}[j]$, such that node $n_k \in N^l_1$ for node $n_l \in \mathcal{C}$ ($n_l \neq n_j$), can be excluded from $\mathcal{U}[j]$, because node $n_k$ is covered by node $n_l$, which is another valid candidate to forwarder. This assertion holds given that all nodes in $\mathcal{U}[j]$ are processed before proceeding to the remaining nodes in $\mathcal{C}$ (i.e., for any node $n_j \in \mathcal{C}$, check this condition for all nodes in $\mathcal{U}[j]$, before proceeding to the next node $n_l \in \mathcal{C}$). Hence, the nodes in $\mathcal{U}$ cover all two-hop and three-hop nodes of node $n_i$. The set of forwarders, $\mathcal{F}_i$, is a subset of nodes in the set $\mathcal{C}$, such that all nodes in $\mathcal{U}$ are covered. On their turn, every node $\{n_{j_1}, n_{j_2}, ..., n_{j_m}\} \in \mathcal{F}_i$ computes its own set $\mathcal{C}$, excluding the sender (i.e., $S = n_i$), and the one-hop neighbors shared with the sender ($N^j_1 \cap N^i_1$), because these nodes are already considered by node $n_i$ when deriving the set $\mathcal{F}_i$. Each node $\{n_{j_1}, n_{j_2}, ..., n_{j_m}\} \in \mathcal{F}_i$ derives its own list of forwarders, i.e. $\{\mathcal{F}_{j_1}, \mathcal{F}_{j_2}, ..., \mathcal{F}_{j_m}\}$ (what can be an empty list in case no candidates lead to three-hop nodes). Each individual set in $\{\mathcal{F}_{j_1}, \mathcal{F}_{j_2}, ..., \mathcal{F}_{j_m}\}$ cover the three-hop neighborhood of nodes $\{n_{j_1}, n_{j_2}, ..., n_{j_m}\}$ respectively. Given that the set of nodes $\{n_{j_1}, n_{j_2}, ..., n_{j_m}\}$ cover the three-hop nodes of node $n_i$, the joint sets $\{\mathcal{F}_{j_1}, \mathcal{F}_{j_2}, ..., \mathcal{F}_{j_m}\}$ cover the four-hop nodes of node $n_i$. Therefore, the set of forwarders chosen subsequently cover all nodes $d + 3$ hops distant from the source, where $d$ is the distance from the forwarder to the source. Because a forwarder is selected by a previous forwarder, or by the source, the set of forwarders is connected. Because the selection process ends when no more three-hop nodes can be reached from a forwarder, it is guaranteed that any node in the network is at most two-hops distant from a valid forwarder.

■

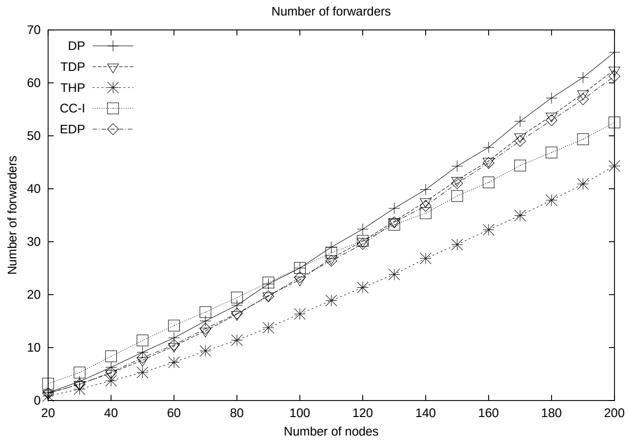


Fig. 2. Number of forwarders varying the number of nodes

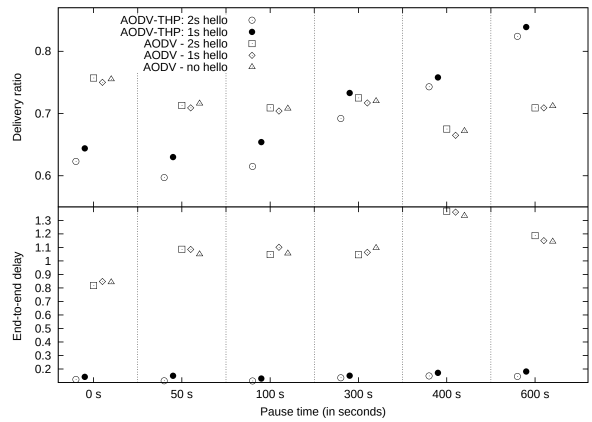


Fig. 3. 50 nodes: Packet delivery ratio, and end-to-end delay

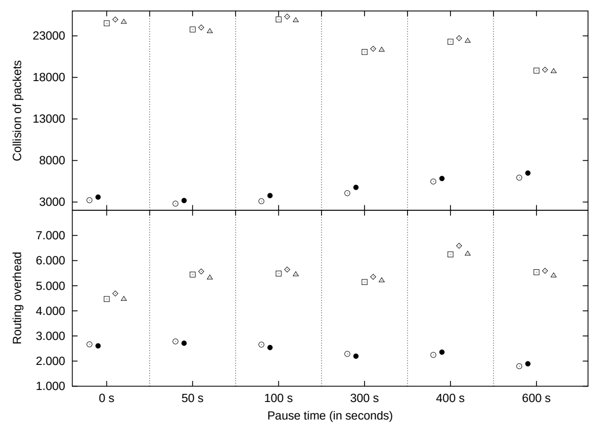


Fig. 4. 50 nodes: Collision of packets, and routing overhead

## III. Efficacy of THP

This section evaluates the efficacy with which THP operates relative to other heuristics, when a TCDS is preferred over a CDS. We use a customized simulator and assume an ideal MAC protocol with which no collisions can occur. This is the same approach adopted in prior work. We compare THP against the best-performing heuristics reported to date, namely DP[2], TDP[3], EDP[4], and Coverage Condition I [5] (CC-I).

We vary the network size and measure the total number of forwarders when computing a CDS (TCDS for THP) of the network. For each configuration we obtain the value for the metric for $500$ arbitrary connected networks. Results represent the average over the $500$ different networks. The network size is varied from $20$ nodes to $200$ nodes. For the same number of nodes, we vary the terrain size accordingly, so that we have an average of $125$ nodes$/km^2$. The radio range is set to $250m$.

Figure 2 shows the average number of forwarders for all broadcast algorithms. The difference between DP and TDP is more noticeable only for larger networks (i.e., more than $100$ nodes). It pays off to have the two-hop neighborhood of the sender (i.e., in TDP) when calculating the set to be covered. EDP and TDP present similar results, but EDP performs better for networks with more than $130$ nodes. TDP performs better than CC-I for networks smaller than $120$ nodes. For all network sizes, THP performs better than the other distributed broadcast algorithms.

## IV. Using THP for Route Discovery

We implemented THP in the AODV[1] routing protocol, in which THP is used in the processing of RREQ. The forwarder list computed via THP is used to select which neighbors should rebroadcast the RREQ. When the RREQ reaches a node which has the destination within its two-hop neighborhood, the RREQ is broadcast locally.

Simulation parameters are similar to those previously reported in [6] for networks with $50$ nodes. There are always $30$ active flows (each lasting in average $30s$, following an exponential distribution). During the simulation time an average of $580$ flows are initiated. Figures 3 and 4 present the simulation results (average over 10 trials).

## V. Conclusions

We presented THP, a localized algorithm for computing two-hop connected dominating sets (TCDS). We showed how THP can be applied to the route discovery process of on-demand routing protocols. The main contribution of THP is that THP reduces the number of redundant broadcast transmission, and we show that THP outperforms the best-performing self-pruning and neighbor-designated algorithms known. When THP is applied to AODV (i.e., AODV-THP) we show that it improves the performance of AODV in all aspects for the case of low mobility.

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