A Tree-Based Approach for the Internet Connectivity of Mobile Ad Hoc Networks

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Abstract: **We propose a tree-based integration of infrastructure networks and MANETs (TIIM) to efficiently extend the scope of mobile Internet protocol to mobile ad hoc networks and devise a tree-based routing protocol (TBRP) that is suitable for the TIIM architecture. Infrastructure networks have a number of fixed Internet Gateways that connect two heterogeneous networks. Mobile nodes form a number of small trees named pMANETs, each of them growing from anchor node which can communicate directly with an Internet Gateway. A new node registers with foreign agent and home agent along the tree path without resorting to an inefficient flooding. Furthermore, the TBRP sets up a routing path efficiently by exploiting the tree information without relying on flooding. We show by resorting to simulation that our approach is competitive against the conventional AODV based approach.**

Index Terms: **Mobile ad hoc network (MANET), mobile IP, mobility management, routing protocol, tree structure.**

I. INTRODUCTION

Mobile ad hoc network (MANET) is temporarily deployed among mobile nodes in a place void of infrastructure elements such as access point (AP) or base station (BS) to which the mobile nodes can directly connect. Despite its broad applications of areas, MANET lacks its applicability in the areas in which mobile nodes need an access to infrastructure networks or communication with mobile nodes of another MANET, or are requested for connection by nodes on other wired or wireless networks. Thus, the scope of mobile Internet protocol (IP) need be extended to include multi-hop wireless nodes; however, it requires management for the current locations of mobile nodes, resulting in a high traffic of control messages.

Recently, a number of researches have been conducted for efficient node mobility management in integrated infrastructure networks and MANETs. Broch *et al.* assume that Internet gateway (IG) is equipped with two network interface cards [1]. One interface that executes standard IP mechanism communicates with Internet nodes while another that does MANET routing mechanism connects to mobile nodes. They use the DSR protocol [2] for a MANET routing. Jonsson *et al.* focus on when to register with FA using MIPMANET Cell Switching algorithm in order to reduce control overhead, and adopt the AODV protocol [9] for a MANET routing. In [3], Sun *et al.* describe how mobile IP and AODV routing protocols can cooperate to discover multi-hop paths between mobile nodes and foreign agents. Prashant *et al.* [4] present a hybrid scheme that combines the techniques such as agent advertisements, TTL scoping and caching of agent advertisements, eavesdropping, and agent solicitation. In [5], Ammari *et al.* propose a three-layer approach that uses mobile IP and DSDV [6], and uses a mobile gateway as an interface between MANET and Internet.

Most of the approaches discussed above resort to an inefficient flooding that causes considerable network overhead for mobility management and/or route discovery. We propose a tree-based integration of infrastructure networks and MANETS (TIIM) to support mobility management and routing and then present a mobility management protocol and a tree-based routing protocol (TBRP) that does not use an inefficient flooding by exploiting the TIIM architecture. The TIIM architecture is composed of a number of small trees, each of them growing from a node that can communicate directly with an Internet Gateway (IG). A new node joins a tree as being a child of some node in the tree and registers with foreign agent (FA) and home agent (HA) along the tree path to which it belongs.

In the design of the proposed protocol, we are pursuing the four aspects: Reducing control overhead, reducing latency to establish a route, balancing the use of two heterogeneous network resources, and increasing communication efficiency. We try to keep the trees as small as possible in order to reduce overhead incurred by various control messages used in network architecture construction and maintenance, mobility management, and route discovery. We can quickly set up a route by exploiting tree information managed at each node and utilizing reliable infrastructure network resources. We notice that infrastructure network can be overloaded if the number of mobile nodes increases largely. Thus, a routing protocol is designed such that a path consists of only mobile nodes if possible. Lastly, we take the distance of two mobile communication parties into consideration upon setting up a routing path. The route is formed by including gateways to increase communication efficiency only if the distance is judged to be relatively long.

Section II describes the network model and some useful definitions. Section III and IV details network management protocol with a new tree-based routing protocol. Performance evaluation is given by resorting to simulation in Section V and followed by concluding remarks in Section VI.

II. PRELIMINARY

A. Network Model

An immobile IG, acting as a FA and/or a HA, has two infrastructure network interfaces, *IF1* to communicate with mobile nodes and *IF2* to communicate with fixed nodes. Two nodes are "connected" when they stay within each other's transmission range. All mobile nodes and IGs can act as a router. We assume

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Table 1. Tree information structure ($TreeInformationTable_i$).

IG		
Anchor		
Parent		
Number of hops to anchor		
Node Status: Anchor, member, orphan		
$D_1{}^1$	Next node leading to D_1	$d_{D_1}{}^2$
D_2	Next node leading to D_2	d_{D_2}
...	...	...

that nodes can overhear packets that are transferred among the other nodes [7]. The network is modeled as an undirected graph G: IGs and mobile nodes are modeled as *nodes*, and connection of two nodes is as an *edge*. $G = (V, E)$, V is a set of nodes and E is a set of edges. $V = V_1 \cup V_2$, V_1 is a set of IGs and V_2 is a set of mobile nodes. $E = E_1 \cup E_2$, $E_1 = \{(x, y)|x \in V_1, y \in V_1, x \text{ and } y \text{ are connected}\}$ and $E_2 = \{(x, y)|x \in V_2, y \in V_2, x \text{ and } y \text{ are connected}\} \cup \{(x, y)|x \in V_1, y \in V_2, x \text{ and } y \text{ are connected}\}$.

- (*Neighbor, Neighbor Set*) Neighbor set, N_i of node i is a collection of neighbor node x such that $(i, x) \in E$.
- (*pMANET*) pico MANET, shortly pMANET, is a connected tree formed by a subset of V_2 where its root node is connected to a node in V_1. A node that belongs to a pMANET is said to be a *member* and a node which is not a member is an *orphan*. A root node being a member is especially called an *anchor*.
- ($NeighborTable_i$) Every node i keeps $NeighborTable_i$ to manage information for each node in N_i. An entry of neighbor j, $NeighborTable_i(j)$ = *(j's ID, j's relationship, j's IG, j's anchor, j's parent, j's distance to j's anchor, j's last updated time), j's relationship* indicates whether j is i's child or not.
- ($TreeInformationTable_i$) Every node i maintains $TreeInformationTable_i$, as shown in Table 1. It holds its IG, its anchor, its parent, its distance to anchor, its node status (anchor, member or orphan), and for each of its descendants, next child node and distance to reach it.
- (*Broadcast, Unicast*) A message is *broadcast* if it is sent to all its neighbors without appointing any specific neighbor; it is *unicast* if it is sent to a specific neighbor. In our implementation, we mostly use "unicast" in transmission that can not only avoid collision, but also detect transmission success or failure quickly by examining the reception of ACK from the MAC layer.

Fig. 1 shows an example TIIM architecture with twenty two nodes (IG100, IG200, 1, 2, 3,$\cdots$, 20). The thick-solid edges and the dotted (or dashed) edges indicate wired connection and wireless connection, respectively. The dashed big circle indicates the transmission range of mobile node and *IF1* in IG and white, shaded, and shaded thick circles represent orphan, member, and anchor, respectively. Nodes 2, 5, 10, and 14 are anchors, forming four *pMANETs*. Each *pMANET* is represented by connected thick dashed edges.

[1] D_n: descendant n.
[2] d_{D_n}: distance to D_n in hops.

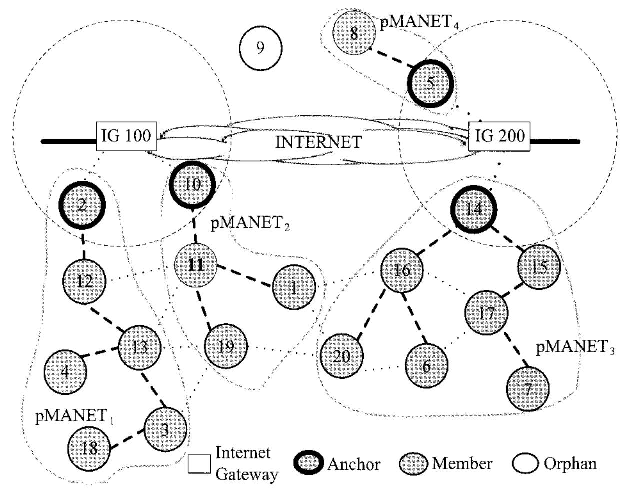


Fig. 1. An example of TIIM architecture.

B. Message Definition

We define some messages to describe network architecture management protocol and routing protocol.

• *MN-Hello, IG-Hello*: Member nodes unicast *MN-Hello* to their parents periodically (orphan node does not send MN-Hello). Anchor being a root node unicasts *MH-Hello* to its IG periodically. The other neighbors overhear the message. *MN-Hello = (MsgId, NodeId, IGId, AnchorId, ParentId, OverCapacity, HopsToAnchor).*

◇ *MN-Hello* message structure (*tocm*: Type of control message, *O*: OverCapacity, *R*: Reserved)

0	4	5 6 7	8 12 16 20 24 28
tocm	O	R	MsgId
NodeId			
IGId			
AnchorId			
ParentId			
HopsToAnchor			

MsgId is a unique message number that the sender generates. A pair <*NodeId, MsgId*> defines a message uniquely throughout the network. *IGId, AnchorId*, and *ParentId* are IG, anchor, and parent to which the sender belong. *OverCapacity* is set to 1 if the sender can not accept child anymore. *HopsToAnchor* is the number of hops from the sender to its anchor. IG unicasts *IG-Hello* periodically to an anchor selected from all the anchors that it manages. If no such anchor does exist, it broadcasts the message. *IG-Hello = (MsgId, IGId, OverCapacity). IGId* is the sender's identification number. *OverCapacity* is set to 1 if IG can not accommodate an anchor anymore.

◇ *IG-Hello* message structure:

0	4	5 6 7	8 12 16 20 24 28
tocm	O	R	MsgId
IGId			

• *AREQ, ARES*: A mobile node that wants to be an anchor selects an IG with its OverCapacity set to 0 among the IG list in its neighbor table and then unicasts anchor request message (AREQ) to the selected IG. *AREQ = (MsgId, SrcId, DstId, UrgentFlag, IGId).*

◇ *AREQ* message structure (*UF*: UrgentFlag)

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										

If a member node is disconnected from its parent or IG and searches for any IG, it sets *UrgentFlag* to 1 and sends the AREQ to an IG. In this case, the receiving IG accepts it as an anchor regardless of its capacity. However, an orphan node does not send AREQ if it does not find an IG with its *OverCapacity* set to 0. If a receiving IG accepts a new anchor, it responds with anchor response message (ARES). *ARES = (MsgId, SrcId, DstId, AcceptedFlag, IGId)* where IG sets *AcceptedFlag* to 1 if it allows a new anchor.

◇ *ARES* message structure (*AF*: AcceptedFlag)

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										

• *JREQ, JRES*: An orphan node that wants to be a member selects a member with its *OverCapacity* set to 0 among the neighbor member nodes in the neighbor table and sends a join request message, *JREQ* to the selected node. If it does not receive join response message (JRES), it sends *JREQ* to another node with its *OverCapacity* set to 0 after some interval. *JREQ = (MsgId, SrcId, DstId, UrgentFlag, IGId)* and *JRES = (MsgId, SrcId, DstId, AcceptedFlag, IGID, AnchorId, HopsToAnchor)*. The usage of AcceptedFlag and UrgentFlag is the same as in AREQ and ARES.

◇ *JREQ* message structure:

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										

◇ *JRES* message structure:

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										
AnchorId										
HopsToAnchor										

• *PCREQ, PCRES*: A member that wants to change its parent sends parent change message (PCREQ) to a selected neighbor with *OverCapacity* = 0. *PCREQ = (MsgId, SrcId, DstId, IGId)*. A receiving node replies with parent change response, *PCRES = (MsgId, SrcId, DstId, IGId, AnchorId, HopsToAnchor, AcceptedFlag)*, where the node sets *AccpetedFlag*[3] to 1 if it accepts a new child.

• *UREQ*: A member sends update request message (UREQ) to notify the change of topology: *UREQ = (MsgId, SrcId, DstId, DirFlag, Action, [IGId, AnchorId, MemberIdList])*. *DirFlag* is set to 0, 1, or 2 if UREQ has to go downward, upward, or in

[3] The OverCapacity of a node that its neighbor maintains can be different from the actual OverCapacity of the node because of Hello interval. Accordingly, parent change request can fail.

◇ *PCREQ* message structure:

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										

◇ *PCRES* message structure:

0	4	5	6	7	8	12	16	20	24	28
tocm		R			MsgId					
SrcId										
DstId										
IGId										
AnchorId										
HopsToAnchor										

both directions, respectively. If *DirFlag* = 0, Action is "Delete" that implies "delete me as a parent since I (sender) become an orphan." The receiving children remove their parent. If *DirFlag* = 1, Action is either "Add" or "Delete." All receiving ancestors have to add or delete the nodes in $MemberList$. If *DirFlag* = 2, Action is "Update" and all receiving nodes have to update node information according to $IGId$, $AnchorId$ and $MemberList$.

◇ *UREQ* message structure (*DF*: DirFlag)

0	4	5	6	7	8	12	16	20	24	28
tocm		Action		R	MsgId					
SrcId										
DstId										
IGId										
AnchorId										
MemberId 1										
...										
MemberId *n*										

III. NETWORK ARCHITECTURE MANAGEMENT PROTOCOL

A. *Neighbor Management*

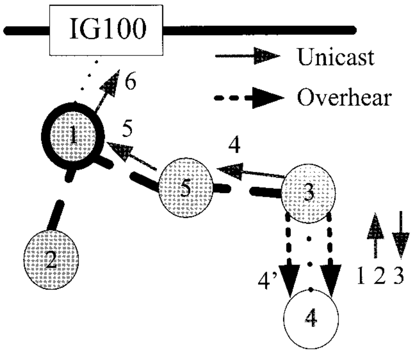
IG selects an anchor among its neighbors and unicasts *IG-Hello* every *Hello-Interval* to the selected node. If it does not receive ACK for *IG-Hello-Retry-Interval*, it selects another anchor and repeats the process. Member (Anchor) sends *MH-Hello* to its parent (IG) periodically. Member or anchor confirms the availability of its upstream link by checking ACK. In this process, all receiving or overhearing nodes update its *NeighborTable*.

B. *Anchor Request Procedure*

An orphan node, upon overhearing IG-Hello from an IG, sends AREQ to the IG in order to become an anchor only if $OverCapacity$ for the IG is 0. The receiving IG responds with ARES if it can accommodate a new anchor. An orphan node becomes an anchor if *AcceptedFlag* in the ARES is 1, and then updates its *TreeInformationTable* by using ARES and the previously received IG-Hello. IG registers the new anchor if it receives ACK against the ARES.

C. *Join Procedure*

Fig. 2 illustrates the join procedure in case that node 4 joins member 3. Node 3, upon receiving JREQ, responds with JRES and updates topology information when it receives MAC ACK. Node 3 sets $DirFlag$ to 2 (bidirectional) and sends



1. Orphan 4 overhears MN-Hello with OverCapacity = 0 from node 3.
2. Send JREQ to node 3.
3. Receive JREQ with AcceptedFlag = 1 from node 3.
4. Node 3 sends UREQ with DirFlag = 2, Action = Update, IGId = 100, AnchorId = 1, and MemberList = {4}.

4'. Node 4 overhears UREQ.

5. Node 5 sends UREQ with DirFlag = 1, Action = Add, MemberList = {4}.
6. Node 1 sends the same msg as node 5 to IG100.

Fig. 2. Join procedure.

UREQ with $Action = Update$, $IGId = 100$, $AnchorId = 1$, and $MemberList = \{4\}$ to node 5. The new node 4 updates its $IGId$ and $AnchorId$ by means of overhearing. Node 5 removes $IGId$ and $AnchorId$, changes $DirFlag$ to 1, and sets Action to "Add" from the received UREQ and then forwards it upward. Node 1 forwards the same message to IG100.

D. Parent-Change Procedure

If member x receives MN-Hello with $OverCapacity = 0$ from its neighbor y, x compares its distance to its anchor and y's distance to y's anchor plus 1. If the difference is not less than T_{change}, x decides the change of its parent and sends PCREQ to y. If x receives PCRES of $AcceptedFlag = 1$, it changes its tree information (parent, anchor, and IG) and sends UREQ that includes its updated information and descendents to its new parent. Its parent sends the UREQ that includes only the $MemberList$ to its ancestors and lets its ancestors and its IG update their tree information. Its children that receive UREQ update the UREQ such that they include the changed anchor and IG and then continue to forward to their respective children. At last, all descendants update a new anchor and IG. The previous parent continues to forward the UREQ that takes $MemberList$ only to its own parent and all the previous ancestors, and IG deletes the nodes by looking up $MemberList$. If T_{change} is set to 1, all nodes will try to keep the shortest distance to IG. The bigger T_{change} is, the more packet transmission overhead the network gets, but the less overhead by parent change it gets.

Let us take a look at information update process when node 4 changes its parent from 5 to 3. Node 4 unicasts UREQ to its new parent 3 with $DirFlag = 2, Action = Update, IGId = 200, AnchorId = 3$, and $MemberList = \{6\}$. Node 3 and IG200 that receive this message add nodes 4 and 6. Node 6 that overhears the same UREQ updates its IG and anchor. Node 5, upon overhearing it, deletes nodes 4 and 6 if its AnchorId and the sender's AnchorId are different and then forwards the message to its parent with the following modifications: $DirFlag = 1$ and $Action = Delete$. Its ancestors 2, 1, and IG100 remove nodes 4 and 6. In this way, node 4 completes topology update by using one UREQ.

E. Tree Link-Failure Repair Procedure

A tree link can be broken due to exhausted power, system failure or node movement. It is extremely critical to detect a broken link quickly in order to correctly maintain tree topology information. A node regards a downlink as broken if it does not receive MN-Hello from the corresponding child for a specified interval, $HelloInterval + \epsilon$, where $\epsilon \ll HelloInterval^4$ is a maximum transmission delay. A node confirms availability of its uplink by checking MAC ACK against its MH-Hello. Note that an anchor sends MN-Hello to its IG. An anchor regards its uplink as broken if it does not receive ACK (MAC Layer) from the IG. Thus, the worst case detection time of broken link for uplink and downlink is $HelloInterval + \epsilon$. IG sends its IG-Hello periodically to one of the anchors that it manages. Because of the downlink failure to the selected anchor, it can either fail to send IG-Hello or it may not receive ACK. In this case, it selects another anchor after some short interval and repeats the same process. The other anchors overhear the IG-Hello. Of course, IG has to broadcast IG-Hello if it does not manage any anchor. Note that broadcast messages being a cause of collision are not used except for this special case.

A node that detects a downlink failure sends UREQ to its ancestors and IG. A node that detects uplink failure becomes a temporary root node (that is not a member but has some descendants) and tries to become an anchor of another IG or join a member by looking up its $NeighborTable$. At this emergency case, $UrgentFlag$ is set to 1 and the node can join any IG or member regardless of $OverCapacity$ value. If it succeeds, it sends UREQ to its ancestors and descendants. It also unicasts UREQ to its new IG or parent with $DirFlag$ = 2. If it fails, it sends UREQ to one of its children and remains an orphan until it overhears MN-Hello or IG-Hello. Each node that receives or overhears the UREQ takes the same process as its parent and can be an anchor, a member or an orphan.

Suppose that link $(12, 13)$ of $pMANET_1$ is disconnected in Fig. 4. Node 12 that detects the downlink failure sends UREQ to its ancestor 2 and IG100. Node 13 that detects the uplink failure finds its neighbor 11 by looking up its $NeighborTable$ and performs emergency join. If it succeeds, node 13 sets $DirFlag$ to 2 and unicasts the UREQ to its new parent 11. Node 11 continues to forward the UREQ after changing $DirFlag$ to 1 that is finally forwarded up to IG100. Its children, 3 and 4 overhears the same UREQ and checks the direction flag. Since $DirFlag$ is 2, node 3 that receives UREQ forwards it to node 18 after changing $DirFlag$ to 0.

[4] We assume that a node sends MN-Hello to its parent successfully every HelloInterval as far as the link is not disconnected, because it does not broadcast a message.

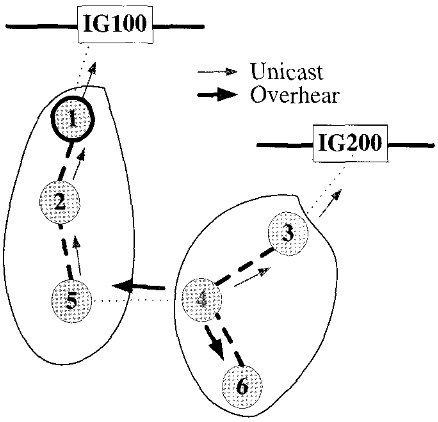


Fig. 3. Parent change procedure.

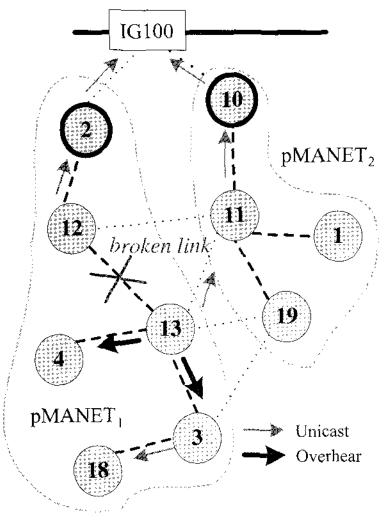


Fig. 4. Tree-link failure repair procedure.

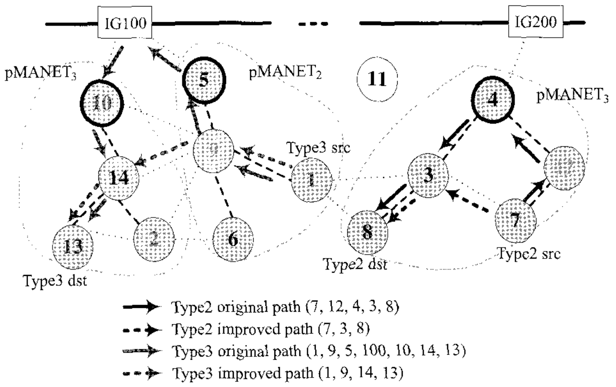


Fig. 5. Route improvement according to path types.

IV. TREE-BASED ROUTING PROTOCOL

In this section, we propose a tree-based routing protocol, TBRP for the TIIM architecture. TBRP protocol consists of path establishment, path improvement, and path recovery. In TBRP, path establishment methods vary according to the relative locations of source (src) and destination (dst).

A. *src on Internet and dst on MANET*

In this case, the routing path is defined as $(src, \cdots, dst.IG, \cdots, dst)$ where src is a wired host on Internet. Supposed that all mobile nodes including dst are registered with FA and HA, no route establishment is needed since the partial path $(dst.IG, \cdots, dst)$ already was established by the network architecture management protocol. Therefore, packets are delivered to dst with the help of Mobile IP.

B. *src on MANET and dst on Either MANET or Internet*

In this case, the routing path is simply defined as $(src, \cdots, src.IG, dst.IG, \cdots, dst)$. Two path segments, $(src, \cdots, src.IG)$ and $(dst.IG, \cdots, dst)$, are maintained by the network architecture management protocol. The routing from $src.IG$ to $dst.IG$ is performed by Mobile IP. Therefore, we do not need any control message to set up the path.

However, the above routing always relies on infrastructure networks. If a number of mobile nodes are very large, it can impose considerable overhead on infrastructure networks. So, if two nodes are mobile, it may be desirable to set up a routing path by utilizing MANET resources only. However, it may not be desirable to set up such a path if two mobile nodes are distanced far away because it will consume MANET resources too much and thus degrade performance in terms of end-to-end delay and delivery ratio. Consequently, we need a method to setup paths such that the utilization of two heterogeneous resources is well balanced by taking performance into consideration.

As a result, instead of using the simple path that always relies on infrastructure resources, we set up various paths depending on the locations of two communication parties as follows.

- Type1: dst is a descendant or neighbor of src.
- Type2: src and dst belong to the same *pMANET* and dst is not a descendant of src (that is, dst is either an ancestor of src or a descendant of its ancestor).
- Type3: src and dst belong to two different *pMANETs* whose gateways are identical.
- Type4: src belongs to a *pMANET* and dst belongs to either Internet or another *pMANET* whose gateway is different.

B.1 Route Establishment

A node that wants to setup a path looks up its *TreeInformationTable* and $NeighborTable$ to see if dst is either its descendent or its neighbor. If that is the case, the path type is a Type1. Type1 path need not be established. Otherwise, src sends route request (RREQ) message toward its IG by following a tree path. While the RREQ is moving upward, every receiving node checks if dst is either itself or one of its descendants. If that is the case, the node replies with route reply (RREP) message, setting up a Type2 path as $(src, \cdots, co\text{-}ancestor, \cdots, dst)$, where $co\text{-}ancestor$ is a common ancestor of both src and dst. Both Type1 path and Type2 path are established within the identical pMANET, utilizing MANET resources only. Considering the locality[5] of MANET communication, the frequency of these

[5]In MANET, it is highly possible that two communication parties reside nearby. This is referred to as a locality of communication.

two path types is expected to be high in reality. The bigger the tree is, the higher the probability of these two path types can be.

If dst is not found until RREQ arrives at $src.IG$, $src.IG$ examines whether or not dst belongs to any other pMANET under its management. If dst belongs to another pMANET, it establishes Type3 path as $(src, \cdots, src.anchor, src.IG, dst.anchor, \cdots, dst)$ and sends RREP including $dst.anchor$ to src. Otherwise, $src.IG$ sends RREQ to dst with the help of Mobile IP and the receiving $dst.IG$ replies with RREP including $dst.IG$ and $dst.anchor$. Type4 path is given as $(src, \cdots, src.anchor, src.IG, dst.anchor, \cdots, dst)$.

B.2 Route Improvement

We improve the path length by using overhearing. While RREQ is moving upward, overhearing nodes checks if dst is either its descendant or neighbor. If that is the case, it can immediately reply with RREP. For example, suppose that $(src, dst) = (1, 13)$ in Fig. 5. Nodes 10, 14, and 2 can overhear the RREQ that node 9 forwards to node 5. Node 2 knows that node 13 is its neighbor and each of nodes 10 and 14 knows that node 13 is its descendant. Thus, they reply with RREP that includes their distance to dst. However, if they send RREP at the same time, delay can be caused by a possible collision. So, we apply grace-delay function d [2]

$$d = h \times (h + r).$$

Here, h is a number of hops from the reply node to dst, r is a value between 0 and 1, and h is a constant value that indicates an inter-hop transmission delay. By this function, a priority of reply is given to a node that has the shortest distance to dst. In consequence, a shorter path (1, 9, 14, 13) or (1, 9, 2, 13) is established instead of the long Type3 path (1, 9, 5, 100, 10, 14, 13).

Consider another case (src, dst) = (6, 13) where two nodes have a common neighbor 2. Node 2 can overhear the RREQ that node 6 forwards to node 9 and then replies with RREP immediately.

B.3 Route Recovery

A routing path can be broken due to link failure in the process of packet transmission. Its recovery is described according to the path types.

- (Type1 path recovery) Suppose that a link (x, y) on Type1 path was broken. In this case, x can detect this broken link by checking ACK immediately after sending a packet to y. Then, x saves the packet in a buffer and sends RREQ of $TTL = 2$ with d_{dst} (distance to dst) waiting for RREP from any node that has a path to dst, possibly a node on $(y, \cdots, dst)$, but has distance not larger than d_{dst} in order to avoid a looping problem. At this case, note that if y is alive, it is highly possible that y stays within two hops. If path recovery succeeds, node x sends the saved packet. Otherwise, x sends route error (RERR) message to src[6]. Then, src initiates route re-establishment after some interval, *Link-Recovery-Time* which takes to fix the broken tree by the network architecture management protocol.
- (Type2 path recovery) Suppose that a link (x, y) on path Type2 was broken. Then, x saves the packet in a buffer and sends RREQ of $TTL = 2$ with d_{dst}, waiting for RREP from any node that has a path to dst, but has distance no larger than d_{dst}. If path recovery succeeds, node x sends the saved packet. Otherwise, x sends route error (RERR) message to src. Then, src re-initiates route establishment after some interval, Link-Recovery-Time which takes to fix the broken tree by the network architecture management protocol.
- (Type3 path recovery) In case of Type3 path, a link on either path segment $(src, \cdots, src.anchor)$ or $(dst.anchor, \cdots, dst)$ can be broken. The recovery process of these two segments is the same as that of Type1 and Type2. However, if (x, y) is $(src.anchor, IG)$, x sends RREQ of $TTL = 2$, waiting for RREP from any anchor or any node that has a path to the IG. The responding nodes use the grace-delay function with respect to IG being an intermediate destination. On the other hand, if a broken link (x, y) is $(IG, dst.anchor)$, x sends RREQ of $TTL = 2$, waiting for RREP from any node that knows a path to dst. If it fails, IG sends RERR to src to re-initiate route discovery.
- (Type4 path recovery) Suppose that a link (x, y) on a path segment $(src, \cdots, src.anchor, src.IG)$. If x is $src.anchor$, it sends RREQ with $TTL = 1$, waiting for RREP from some other IGs or members that know $src.IG$ but are not its descendant. If x is one of the other mobile nodes, the recovery process is the same as that of Type2 path.

[6]Route recovery can be performed after sending RRER to src; however, since the local route recovery is performed with $TTL = 2$ without delay, doing local recovery first will make packets flow smoothly.

V. PERFORMANCE EVALUATION

We used the QualNet 3.9 network simulator, a commercial version of GlomoSim. 103 nodes (100 mobile nodes and three IGs) are placed in a square zone: 100 mobile nodes are randomly distributed and 3 IGs take the predefined positions. In the terrain of $1000 \times 1000 (\mathrm{m}^2)$, scenarios $1, \cdots, 4$ use different IG positions as in Figs. 6(a)–(d), respectively while the 5th scenario is the same as scenario 1, but has the bigger terrain, $1500 \times 1500 (\mathrm{m}^2)$.

Considering the IG distribution patterns for different scenarios, an IG with the bigger coverage will have more anchors and thus get more trees. Consequently, it will have the smaller size of trees, shortening the distance from each member to IG. From this viewpoint, we can judge that the IG distribution in scenario 1 is the best of all. On the contrary, note that the IG located at the corner has only one quarter of coverage of that in the middle. Thus, scenario 4 is considered the worst.

A. Scenario Properties and Performance

Simulation was run to evaluate the structural characteristics of TIIM for the five scenarios with the parameter values of Table 2 and variations of maximum node speed from 0 to 25m/s. Each metric was given an average value from ten runs of simulations

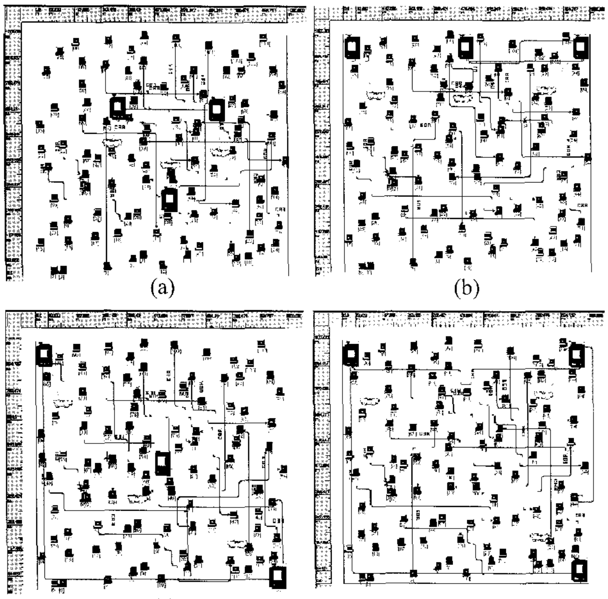


Fig. 6. Four deployment scenarios for 3 IGs: (a) scenario 1, (b) scenario 2, (c) scenario 3, and (d) scenario 4.

Table 2. Simulation parameter values.

Parameters	Value
Mobility pattern	Random waypoint
Pause Time	0
Number of nodes	103 (3 fixed IGs included)
Dimension	1000×1000, 1500×1500
Transmission range	250 m
Wireless nandwidth	2 Mbps
Traffic pattern	CBR
Number of sessions	15 (1 packet/sec.)
Packet size	512 bytes
Simulation time	600 seconds

with different seed values. In graph notation, we denote scenario n with k dimension as S_{n-k} where $n = 1, \cdots, 4$ and $k = 1000 \times 1000$ or 1500×1500.

Take a look at Figs. 7 and 8. According to Fig. 7, it is shown that the number of trees decreases slightly with the increase of node speed. This is due to the transiently increased number of orphan nodes. $S1 - 1000 \times 1000$ in which IGs cover the biggest area shows the largest number of trees, leading to the smallest average tree size. As we expected, $S4 - 1000 \times 1000$ shows the smallest number of trees, resulting in the largest average tree size. The number of trees in $S1 - 1500 \times 1500$ is almost half as large as that of $S1 - 1000 \times 1000$ because its low node density allows the less number of anchors.

In proportion to the coverage area of IGs, the average number of trees is given in the order of $S1$, $S3$, $S2$, $S4$, but the size of trees is in the reverse order. In general, the size of tree is closely related to network overhead as shown in Fig. 9. However, comparing $S2 - 1000 \times 1000$ and $S4 - 1000 \times 1000$, the former with the smaller size of tree shows the higher overhead than the latter. The reason is that nodes are prone to join the IG in the middle

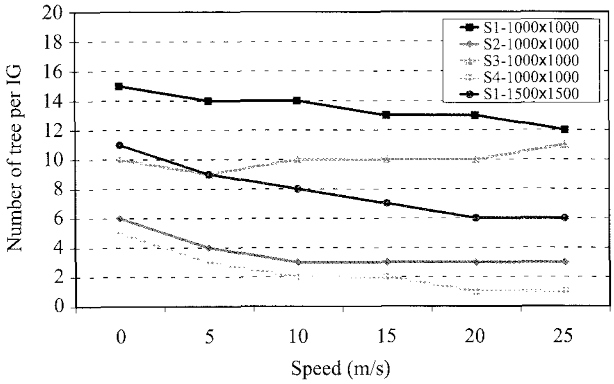


Fig. 7. Average number of trees per IG with variation of maximum node speed.

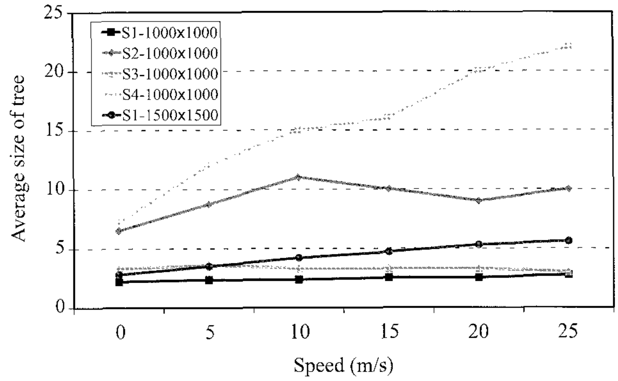


Fig. 8. Average size of tree with variation of maximum speed.

in view of the IG deployment of $S2 - 1000 \times 1000$. Accordingly, the pMANETs that belong to the middle IG can be large. Referring to Fig. 10, delivery ratio is in a reciprocal proportion to network overhead. Also, note that $S1 - 1500 \times 1500$ shows overhead much higher than $S1 - 1000 \times 1000$ because of its high probability of link destruction as in Fig. 9.

Fig. 11 shows how much infrastructure network resource is used in the communication of two mobile nodes. According to the simulation result, we can see that 25% to 58% of communications uses only MANET resource depending on node speed, even in $S1 - 1000 \times 1000$. The reason that we have the largest value in $S2 - 1000 \times 1000$ is that we can have the largest number of Type1 or Type2 paths due to the increased size of the trees grown from the IG in the middle. However, in case of $S4 - 1000 \times 1000$, the sizes of trees will be almost even since three IGs are all located in the corner, resulting in the lower MANET-Only utilization. Furthermore, we can see that the MANET-Only resource utilization ratio decreases since MANET becomes unstable with the increased speed.

According to the simulation study, it was proven that $S1$ has the best IG distribution. Now, let us compare $S1 - 1000 \times 1000$ and $S1 - 1500 \times 1500$. $S1 - 1500 \times 1500$ has less number of anchors (trees) due to its reduced node density. So, $S1 - 1500 \times 1500$ shows the increased average size of tree and thus the increased overhead compared to $S1 - 1000 \times 1000$, resulting in much less delivery ratio as in Fig. 10. Also, $S1 - 1500 \times 1500$ shows a slightly higher decrease in delivery ratio as node speed

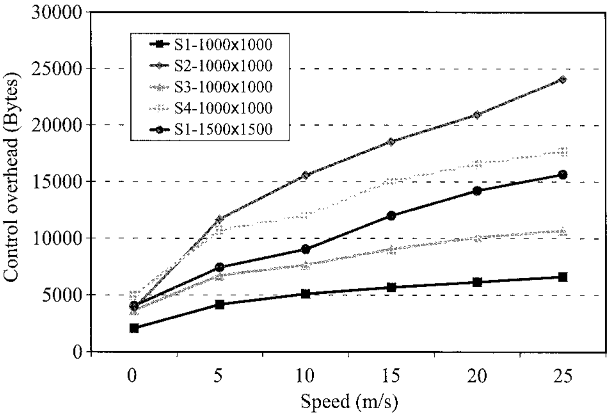


Fig. 9. Control overhead of variation of maximum node speed.

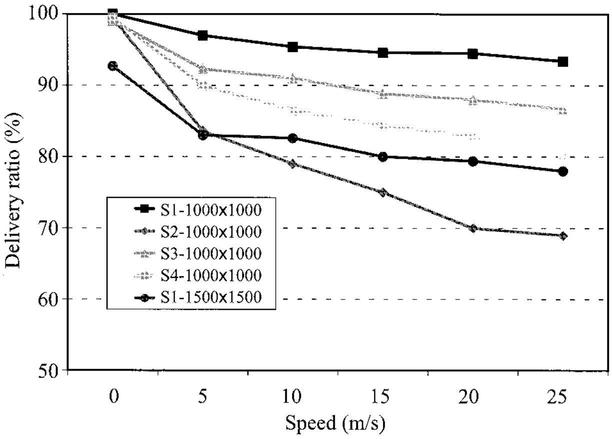


Fig. 10. Delivery ratio with variation of maximum node speed.

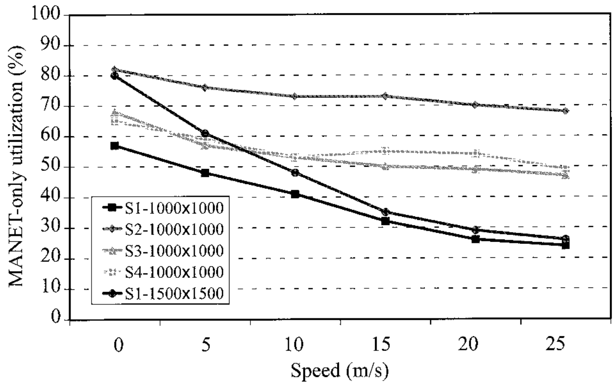


Fig. 11. MANET-Only resource utilization.

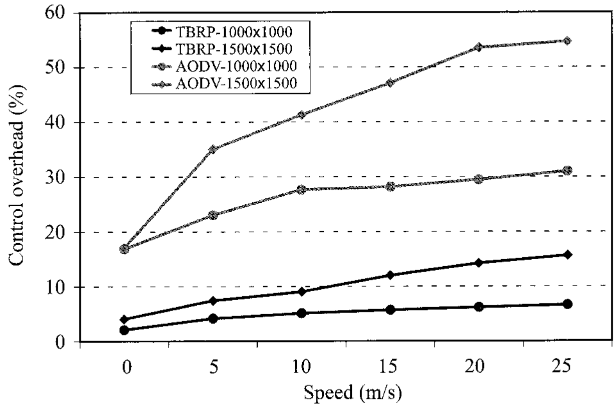


Fig. 12. Control overhead with variation of maximum node speed: TBRP vs. AODV.

increases. This is because the network becomes unstable due to the loose connectivity among mobile nodes. The MANET-Only resource utilization in $S1-1500 \times 1500$ with the big trees is higher than that of $S1 - 1000 \times 1000$ since the former will have the increased number of Type1 and Type2 paths. However, node connectivity in $S1 - 1500 \times 1500$ is more likely to be broken because of its loose connectivity. So, its MANET-Only utilization decreases rapidly because communication will have a higher dependency on IGs with increased node speed.

B. Performance Comparison

We evaluated our approach against the AODV based protocol [3]. It uses a hybrid mobility management approach which mixes both proactive and reactive ones for the efficiency of mobility management. IG floods an agent advertisement message periodically up to k_1 hops. A reverse path from any receiving node to the IG is established while the advertisement message is being moved. Any unregistered mobile node that receives the advertisement message sends a registration request message along the reverse path to register with HA and FA. A forward path from IG to a mobile node is established while the registration request message moves. A data packet is delivered to a registered mobile node along the forward path. The IG that receives a registration request message registers the mobile node with FA and HA. After completion of registration, the path is regarded as a valid one until the corresponding timer expires.

A mobile node that is distanced over k_1 hops and thus does not receive an agent advertisement message floods agent solicitation message with $TTL = k_2$ in order to find any previously registered node. In this process, the forward path from the receiving node to the node that initiated the agent solicitation message is established. The previously registered node that receives the agent solicitation message sends a response message whose moving establishes the reverse path. Accordingly, a mobile node that has not been registered yet can register with FA and HA along the combined two partial reverse paths.

A node that wants data transmission first examines whether the destination is in its routing table or not. If the path is fresh, it starts sending packets. Otherwise, if it is stale, the source floods RREQ with the old TTL in the routing table to explore a new path. Meanwhile, if a source has not known the destination so far, it floods RREQ with $TTL = 1$. If it does not receive RREP from either the destination or any IGs, it increases TTL by 2 and floods RREQ. This repeats until TTL reaches $TTL_{threshold}(= 7)$. If source still fails to receive RREP, it sets TTL to AODV_DEFAULT_NET_DIAMETER (= 35) and floods RREQ as a last resort.

We used two scenarios $S1-1000\times1000$ and $S1-1500\times1500$ to compare two approaches. In case of TBRP, we took three types of messages into account in overhead computation: Hello

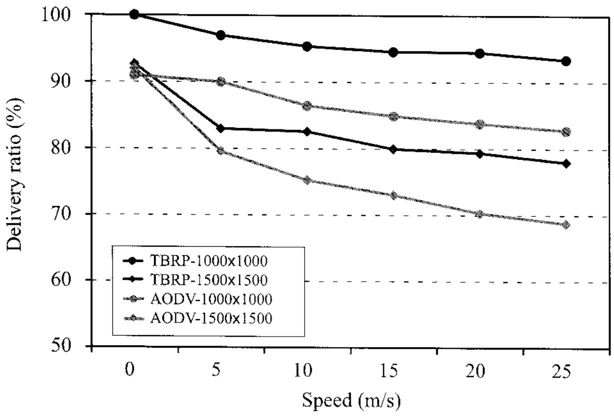


Fig. 13. Delivery ratio with variation of maximum node speed: TBRP vs. AODV.

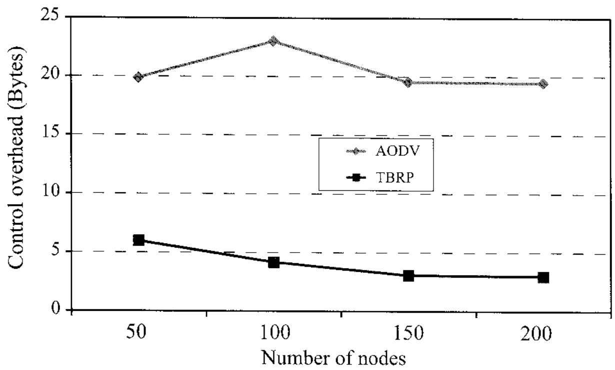


Fig. 14. Control overhead with variation of nodes: TBRP vs. AODV.

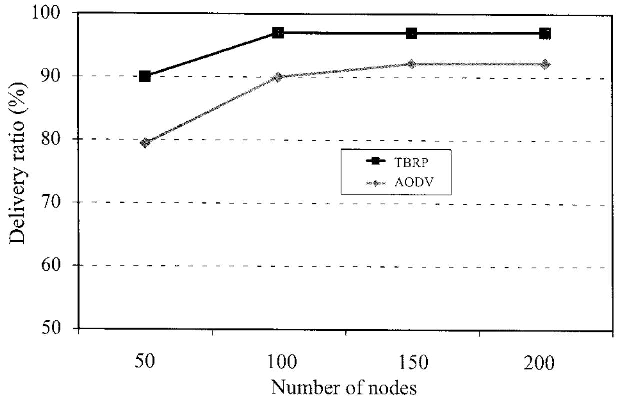


Fig. 15. Delivery ratio with variation of nodes: TBRP vs. AODV.

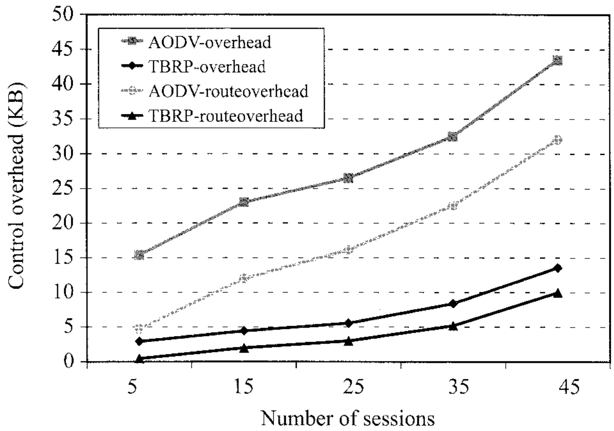


Fig. 16. Control overhead with variation of sessions: TBRP vs. AODV.

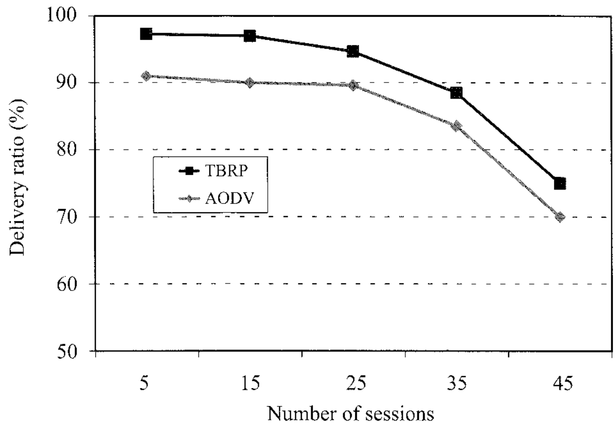


Fig. 17. Delivery ratio with variation of sessions: TBRP vs. AODV.

message that each node sends every two seconds, messages to form and maintain the TIIM architecture, and messages to establish a route. In Fig. 12, we see that TBRP induces much less overhead than the AODV approach (for AODV, we set k_1 and k_2 to 3 and 2, respectively which show the best performance). This is because our approach does not use a flooding in both mobility management and routing protocol. As a result, TBRP showed good improvement in delivery ratio by about 12% overall.

Another simulation was conducted by varying the number of nodes as 50, 100, 150, 200 nodes with terrain 1000m $\times$ 1000m and maximum speed 5 m/s. Fig. 14 shows that TBRP induces much less overhead than AODV, showing about 12% gain of delivery ratio overall as shown in Fig. 15. When the number of nodes is 50, AODV shows a low overhead because nodes can be isolated or network can be partitioned transiently, reducing the range of RREQ. However, delivery ratio is quite sensitive to the traffic due to the increase of overhead as in Fig. 16 and Fig. 17. We can easily identify that the increase of overhead is due to the route overhead caused by RREQ, RREP, and RRER. However, overhead by RREQ in TBRP is relatively low compared with that by the other messages (include architecture management control messages). This is because we exploit formation in establishing a path. Considering that almost 50% of nodes participate in active communications for 25 sessions, our protocol is quite competitive.

VI. CONCLUDING REMARKS

We proposed the TIIM architecture to expand Mobile IP for the support of MANET, network architecture management protocol to form and manage the TIIM architecture, and then the TBRP as a routing protocol suitable for the TIIM architecture. Mobile nodes form a number of small trees called pMANETs, each of them growing from an anchor node that is able to communicate directly with an IG. Mobile node can easily register with FA and HA along the pMANET paths without using an inefficient flooding. pMANETs are maintained such that all members maintain the shortest path to their IG. The TBRP sets up and optimizes a routing path efficiently by exploiting the tree information of the TIIM architecture. It does not use an inefficient flooding, either. We showed the competitiveness of the proposed protocol by comparing with the well-known AODV based approach.

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