

Mobile IPv6-Based Ad Hoc Networks: Its Development and Application

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Abstract—The Internet protocol version 6 (IPv6)-enabled network architecture has recently attracted much attention. In this paper, we address the issue of connecting mobile ad hoc networks (MANETs) to global IPv6 networks, while supporting IPv6 mobility. Specifically, we propose a self-organizing, self-addressing, self-routing IPv6-enabled MANET infrastructure, referred to as IPv6-based MANET. The proposed self-organization addressing protocol automatically organizes nodes into tree architecture and configures their global IPv6 addresses. Novel unicast and multicast routing protocols, based on longest prefix matching and soft state routing cache, are specially designed for the IPv6-based MANET. Mobile IPv6 is also supported such that a mobile node can move from one MANET to another. Moreover, a peer-to-peer (P2P) information sharing system is also designed over the proposed IPv6-based MANET. We have implemented a prototyping system to demonstrate the feasibility and efficiency of the IPv6-based MANET and the P2P information sharing system. Simulations are also conducted to show the efficiency of the proposed routing protocols.

Index Terms—Addressing, global connectivity, Internet protocol version 6 (IPv6), mobile ad hoc network (MANET), routing.

I. INTRODUCTION

WITH THE rapid development in wireless communications in recent years, the necessity for sufficient Internet protocol (IP) addresses to meet the demand of mobile devices, as well as flexible communications without infrastructure, are especially considerable. The next-generation IP, Internet Protocol version 6 (IPv6) [1], [2], provides sufficient IP addresses to enable all kinds of devices to connect to the Internet and promotes mobile wireless commerce (m-commerce). The IPv6-enabled network architecture will become the future standard. Additionally, most current mobile devices are equipped with IEEE 802.11 wireless local area network (WLAN) interface cards. IEEE 802.11 WLAN supports two operating modes: infrastructure mode and ad hoc mode. The infrastructure mode requires all mobile devices to directly communicate to the access point (single-hop communication). In the ad hoc mode, mobile devices dynamically form a mobile ad hoc network (MANET) with multihop routing. Clearly, the ad hoc mode

allows for a more flexible network, but its aim is not to connect to the Internet. In this paper, we address the issue of connecting MANETs to global IPv6 networks while supporting IPv6 mobility.

Much attention has been paid to IP address autoconfiguration and IPv6 extension for MANETs [3]–[5] in recent years. IPv6 autoconfiguration mechanism [3], [4] allows a node to generate a link-local IP address. Extension has also been made to be suitable for MANET [5]. However, global connectivity for a mobile node is not supported in [5]. Later on, [6] and [7] address how to provide global connectivity for an IPv6-enabled MANET. In these works, a MANET node can acquire a global IPv6 address from an Internet gateway, and then access to the Internet through the gateway. Routing in MANETs and the IPv6 network is based on existing protocols.

Currently, existing MANET unicast routing protocols, such as ad hoc on-demand distance vector (AODV) [8], destination-sequenced distance vector (DSDV) [9], optimized link-state routing protocol (OLSR) [10], and zone routing protocol (ZRP) [11], typically only maintain routes locally within the reach of a MANET and, thus, do not consider global connectivity. Surprisingly, only few studies [12] have so far been made on IPv6-enabled routing. AODV applies the embedding of Internet connectivity acquisition to support IPv6, referred to as AODV6 [12]. AODV6 adopts hierarchical routing to support IPv6 mobility, in particular, care-of-address (COA), and flat routing within a MANET. Clearly, most of past researches mainly focus on routing in general large-size MANET and separate the addressing protocol from routing protocol. However, in reality, we anticipate the scenario of many small-size MANETs connected to the global Internet via access routers (ARs). In this paper, we shall integrate the routing and addressing protocols for small-size, low-mobility MANETs such that routing overhead can be reduced and unique address for each mobile node can be easily acquired.

In this paper, our goal is to allow mobile nodes form an IPv6-based MANET flexibly and access the global IPv6 Internet easily and efficiently. To achieve this goal, we first propose a novel mechanism to allow IPv6 mobile nodes to form a self-organizing, self-addressing MANET into a tree structure rooted with an Internet gateway, referred to as the AR, as shown in Fig. 1. The forming of MANET extends the coverage of the AR. In other words, it allows a mobile node to access to the Internet even it cannot directly communicate with the AR. Each MANET is formed by mobile devices in a small geographic area, such as a meeting room, a building, or a train. Within a MANET, each mobile device will move around, but only at walking speed (low mobility, less than 2 m/s). Mobile IPv6

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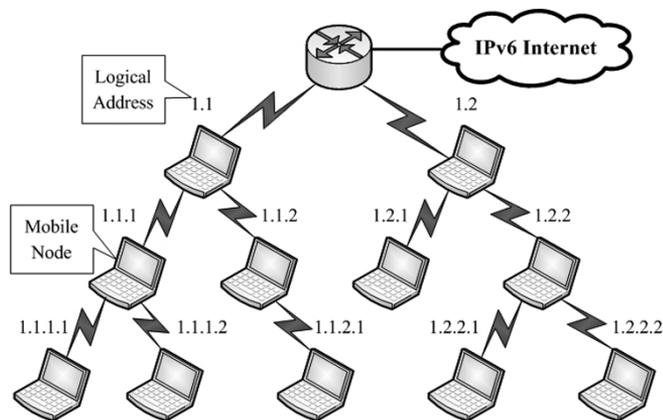


Fig. 1. A self-organizing, self-addressing, self-routing IPv6-based MANET.

will be supported such that a mobile node can move from one MANET to another. Next, specially designed unicast/multicast routing protocols for MANETs, which are more suitable for IPv6, will be proposed. In our design, a MANET under an AR is viewed as an IPv6 subnet which uses the AR as the default router to access the global IPv6 Internet. Full functionality of IPv6/ICMPv6 [13] is supported on the ad hoc network such that each mobile node can perform stateless IPv6 address autoconfiguration.

Since multicast is mostly used by ICMPv6 [13] in IPv6 networks, the proposed multicast routing protocol utilizes the feature of ICMPv6 messages, as well as the special topology of the MANET. There exist several tree-based multicast routing protocols for MANET, e.g., AMRoute [14], AMRIS [15], and LAM [16]. However, they all have distinct purposes from ours. Those approaches consume excessive overhead to maintain a great quantity of source trees. However, the proposed multicast routing, based on flooding, efficiently reduce the flooding messages by utilizing the tree topology of the MANET. The direction of ICMPv6 messages also can be utilized to reduce flooding. For example, router advertisement (RA) messages are sent from the AR to all nodes in the subnet. Therefore, the flooding of RA messages should be only forwarded to child nodes on the tree and stop at the leaf nodes.

Similar to the importance of IPv6 in the next-generation Internet, peer-to-peer (P2P) applications are very likely to be the killer applications in the future. Passive Distributed Indexing (PDI) [17] and Optimized Routing Independent Overlay Network (ORION) [18] have studied the issue of P2P information sharing on a MANET. PDI can efficiently search files scattered over mobile devices by querying locally. ORION combines application-layer query and overlay network construction with network-layer route discovery to ensure accurate search and low overhead. Both of these researches use the flooding mechanism to find files on demand. But these solutions are not scalable and curtail throughput as the size of a MANET grows. Therefore, we also designed a distributed, but structured P2P information sharing system over our IPv6-based MANET using the distributed hashing table (DHT) technique. Note that this design is under the assumption that mobile nodes only move in low speed.

Feasibility and efficiency of the proposed IPv6 based MANET are also evaluated in this paper. We demonstrate the feasibility of the IPv6-based MANET via prototyping a real system. The proposed tree overlay construction and maintenance protocols, unicast/multicast routing protocols, and P2P information sharing system on IPv6-based MANET are implemented. In addition, we evaluate performance of proposed routing protocol via simulations. The performance of the proposed unicast routing protocol outperforms that of OLSR and DSDV. We also show that the performance of the proposed multicast routing protocol is more efficient than that of the basic flooding approach.

The rest of this paper is organized as follows. Section II presents the main design principles of IPv6-based MANET. A prototyping system implementation details are given in Section III. Performance evaluation results are shown in Section IV. Finally, Section V follows with a concluding remark.

II. OVERVIEW OF THE PROPOSED IPV6-BASED MANET

In this section, we give an overview of the proposed IPv6-based MANET. To construct an IPv6-based MANET, we propose a self-organizing addressing protocol to organize nodes into a tree structure. The logical address of a node is automatically configured when it joins and leaves. Based on the tree topology, we then propose a new routing protocol, which is based on longest prefix matching and soft state routing cache. IPv6 is supported on MANET such that each mobile node automatically configures its global IPv6 address and connects to the global Internet via an AR. Meanwhile, Mobile IPv6 is also supported to allow a mobile node to move from one MANET to another. Finally, we also show how to construct information sharing applications on the IPv6-based MANET. In the following, we shall describe more detail information of each proposed mechanism.

A. MANET Tree Overlay Management

In this paper, we consider that a MANET is formed by nearby mobile nodes which access to the Internet via an AR, as shown in Fig. 1. In this section, we describe how mobile nodes automatically form a tree overlay and configure their IPv6 addresses. Specifically, we will describe procedures for a mobile node to join the tree overlay, configure its IPv6 addresses, and maintain the tree overlay.

1) *JOIN Procedure*: Fig. 2 shows the flow chart of the JOIN procedure. When a node joins the MANET, it sends out a JOIN REQUEST message to its neighbors. Each neighbor of the new node that is already on the tree topology will select a unique address among its current child nodes and response the JOIN message with the selected address. The logical address of a mobile node indicates its location on the tree. Specifically, upon receiving a JOIN request, a neighbor node with address x_1, \dots, x_i will select an address x_1, \dots, x_i, x_{i+1} , which is the smallest and unique id among that of its child nodes, for this new node. If the new node does not receive any response within a fixed time, it will keep sending the JOIN REQUEST message until it got a response. On the other hand, the new node may receive one

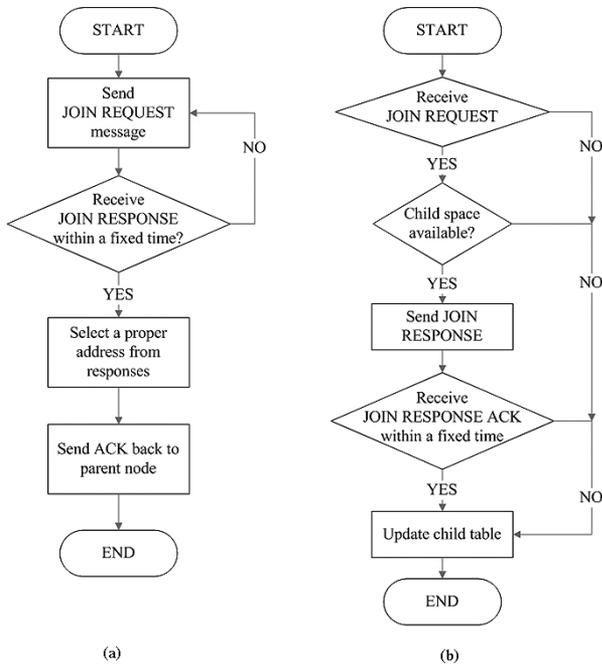


Fig. 2. Flow chart of JOIN procedure. (a) New node joins in network. (b) Neighbors response to address assign.

or more responses from its neighbors. In this case, it selects the most “appropriate” address from one of the responses and sends back an ACK. The criteria for selecting the most “appropriate” address may be the one near the tree root, with higher signal strength; or the sending node has more power or less mobility. In this paper, we prefer to select the one near the tree root, because it results in a flat tree which yields shorter routing path.

2) *IPv6 Address Configuration*: Each mobile node will configure its IPv6 address according to its logic address. According to the literature, a mobile node may configure its IPv6 link-local or global address by attaching a network prefix to its 64-bit network interface ID, as shown in Fig. 3(a). However, this could make routing in MANET quite difficult and independent of IPv6. In this paper, we propose to use a mobile node’s logic address as its 64-bit interface ID when configuring its IPv6 addresses (link-local or global), as shown in Fig. 3(b). The 64-bit interface ID is divided into sixteen levels, each with four bits. That is, each node can have at most 15 child nodes, and the height of overlay tree is at also most 16. For example, if the logical address of a node is “1.2.1,” its link local address will be set to FE80::1210:0:0:0/64. Note that this addressing space should be abundant for any possible MANET under consideration. (That is, a MANET under an AR.)

3) *Maintain the Tree Overlay*: Heartbeat (in a child) and child timer (in a parent) are used to monitor each other’s status. In order to make the routing efficient and maintain the tree structure, each node regularly sends a heartbeat to its parent node after it has joined the network, as shown in Fig. 4(a). Normally, the node should receive an ACK from its parent. However, if a child node does not receive the ACK message within a predefined time, it increases its heartbeat-ACK-missed counter by one. If the counter is larger than a certain threshold, it assumes that its parent has crashed or moved away. In this case, the node

should restart the JOIN procedure. On the other hand, upon receiving a heartbeat from a child, the parent node will reset the corresponding child-heartbeat timer. If a child does not send a heartbeat for a long time, the child-heartbeat timer will expire. In this case, the parent node assumes that the child has crashed or moved away. The resource and address of the child will then be released. The flow chart for maintaining the status of child nodes is shown in Fig. 4(b).

B. Routing Protocol

Based on the tree topology, we propose a novel routing protocol for the proposed IPv6-based MANET. To avoid additional overhead, the proposed routing protocol does not need to find routing path on demand. Each mobile node maintains a routing table with two kinds of information: default routing and soft state routing cache.

1) *Unicast Routing Protocol*: A mobile node in the proposed MANET will have information of its parent and child nodes used for default routing, as there exists at least one path between any two nodes on the tree. Longest prefix matching is used to determine how to forward a packet to its destination. However, packets routed through the tree structure may have a relatively longer path or delay latency. Using Fig. 5 as an example, a packet sent from node “1.1.1.2” to node “1.1.2.1” will be routed through the hierarchical path, which traverses node “1.1.1,” node “1.1,” node “1.1.2,” and node “1.1.2.1.” In this case, the route length is four hops but the destination is just one hop away from the source. The soft state routing cache ameliorates this problem.

Each mobile node can improve the routing efficiency by adding its neighbor information into the routing cache. Each node can collect information of its one-hop-away neighbors by listening to the air. Therefore, a routing cache with information of one-hop-away neighbors can be built without any routing information exchange. Due to the mobility of mobile nodes, each entry of the routing cache is associated with an age timer so that obsolete information can be deleted. (So the routing cache is a soft state cache.) Routing is still based on longest prefix matching, but the routing table is expanded with routing cache. Therefore, a shortcut can be taken when forwarding packets. For example, in Fig. 5, a routing path with routing cache from node “1.1.1.2” to node “1.1.2.1” will be routed within one hop.

2) *Multicast Routing Protocol*: Multicast is especially important for sending ICMPv6 messages. Multicast routing in the proposed MANET is quite straight forward by using flooding and utilizing the tree structure for a quicker stop. When a mobile node sends a multicast packet, it forward the packet to its neighbors. Each intermediate node, which is not a leaf node of the tree, that receives a multicast packet for the first time should forward the packet to its neighbors. Each multicast packet can be uniquely identified by its source node and unique sequence number. Clearly, the forwarding process will broadcast the packet to all nodes on the tree and stop at the leaf nodes. Since the tree is expected to be a short and wide tree, the number of leaf nodes is expected to be around 1/2 of the number of all nodes. As a consequence, a multicast packet will be forwarded only around 1/2 of the nodes. This multicast approach is referred to as the default multicast.

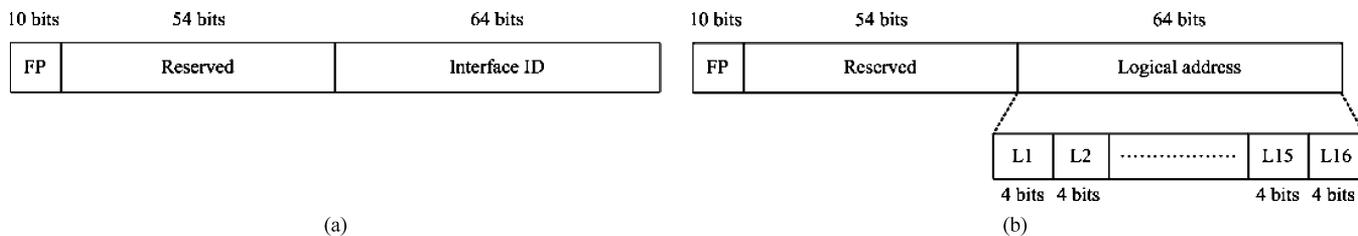


Fig. 3. IPv6 link local address. (a) Original. (b) Modified.

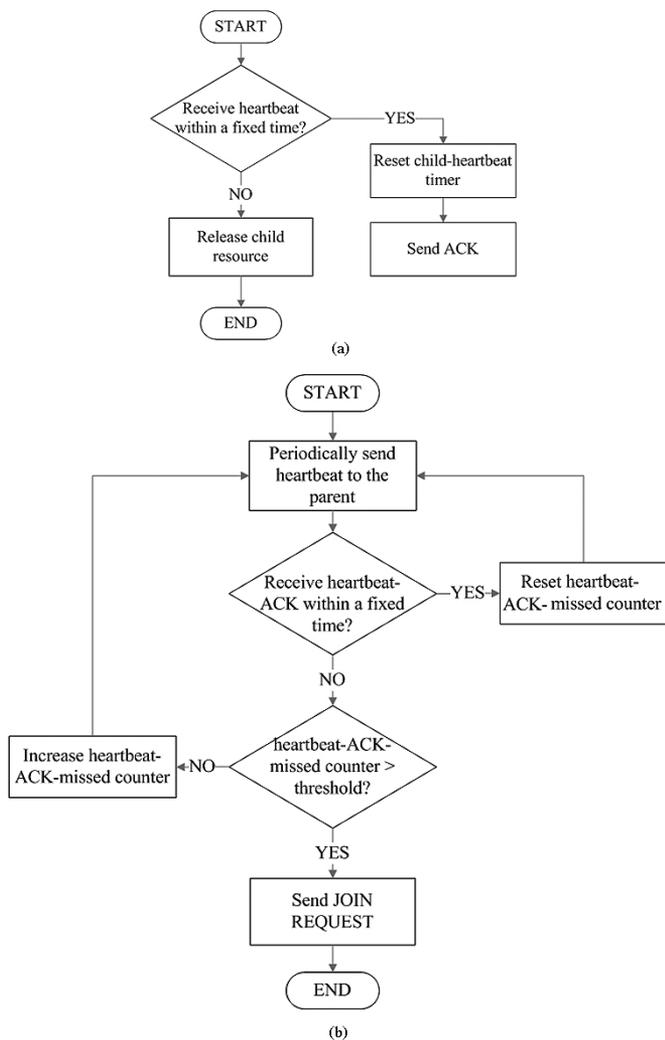


Fig. 4. Flow chart of tree overlay maintenance. (a) Child maintenance at the parent node. (b) Parent maintenance at the child node.

However, after analyzing the ICMPv6 messages, we observe that unidirectional multicast can fulfill the desired task and is much more efficient. ICMPv6 messages can be classified into three categories: send from router to all nodes, send from a node to all routers, and send from a node to other nodes. Some of unique features of our IPv6-based MANET make the task much easier. First, there is only one router, i.e., the AR, which is also the tree root, in a MANET. Second, the unique address of each node can be ensured by the addressing scheme, as shown in Section II-A2. Therefore, the three types of multicast messages become: send from the AR to all nodes in MANET, send

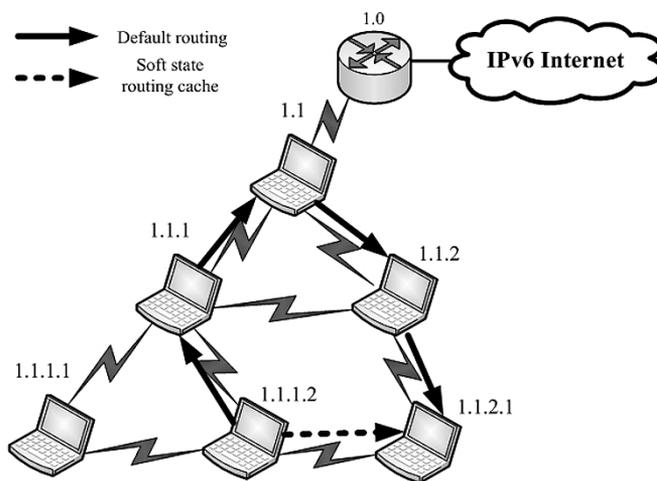


Fig. 5. Example of routing path selection.

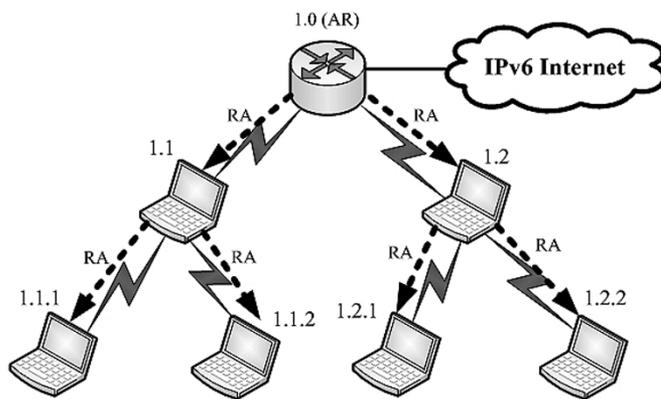


Fig. 6. Example of multicast routing.

from a mobile node to the AR, send from a mobile node to other nodes. The first type of message, such as RA messages, is sent from the AR to all its child nodes. Each intermediate node then should only forward the packet to its child nodes. So, it is forwarded in one direction, from parent nodes to child nodes, as shown in Fig. 6. The second type of message, such as router solicitation (RS) messages, is sent from a node to the AR. The node should send the message to its parent node and its parent node should forward the message to its parent node only, until the AR. Therefore, the packet is also forwarded in the direction from child nodes to parent nodes. The third type of message, such as Neighbor Solicitation (NS) message, is mainly used for neighbor discovery [the Duplicate Address Detection (DAD)

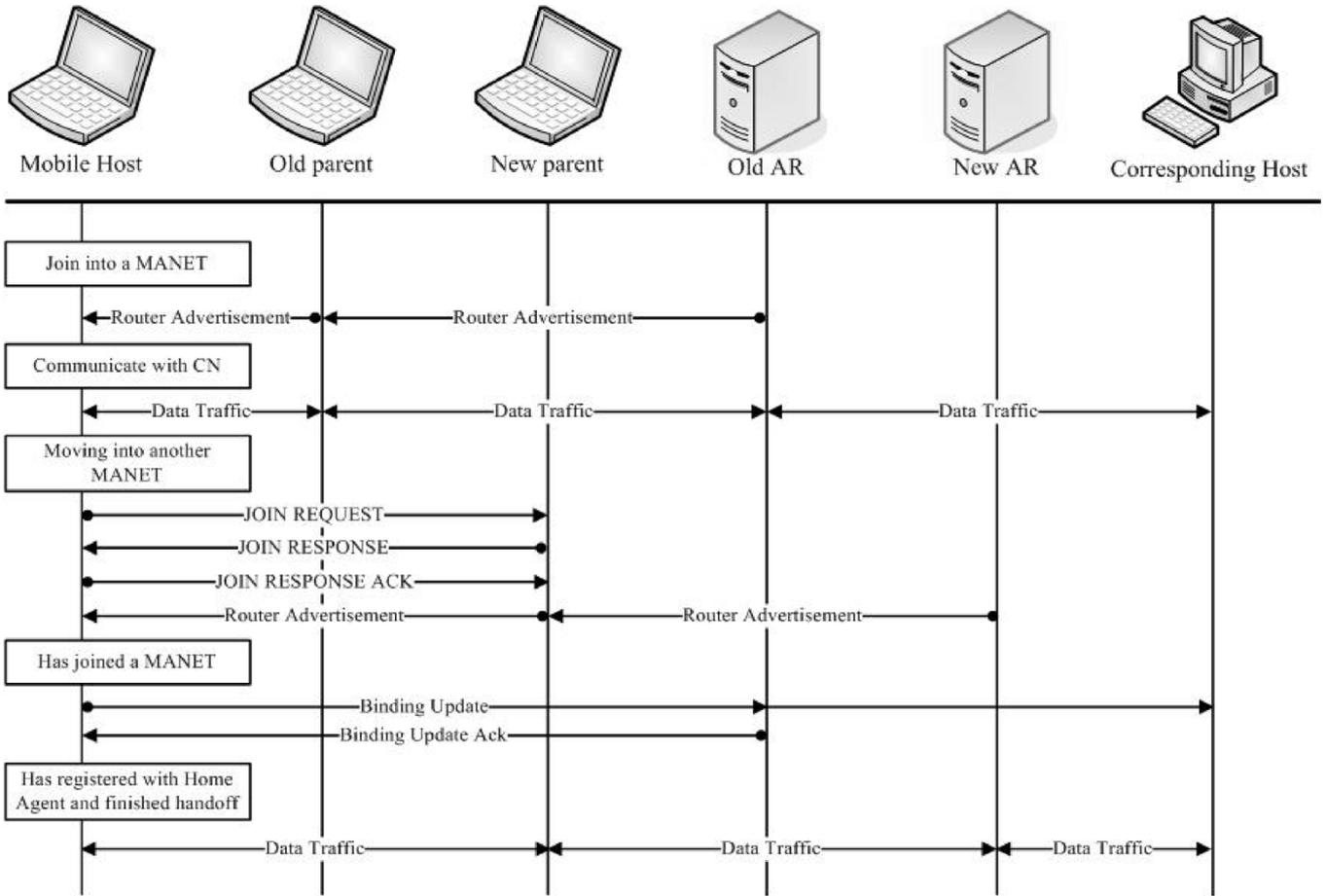


Fig. 7. Procedure of handoff.

protocol]. Since the logic address is guaranteed to be unique in the MANET, it is not necessary to guarantee the message to be sent to all nodes. Therefore, the unidirectional multicast is performed as follows. A direction flag, which can be set to up, or down, is added in each multicast packet. The direction flag of a multicast packet sent by the AR, or a mobile node, is set to down, or up, respectively. The packet is then forwarded to its neighbors. At each intermediate node, a multicast packet will be forwarded if and only if the packet is sent from its parent or child nodes. If the multicast packet is received from its parent node and the direction flag is down, the packet will be forwarded to its child nodes with direction flag set to down. On the other hand, if the multicast packet is received from one of the mobile host’s child nodes and the direction flag is up, the packet will be forwarded to its parent node with direction flag set to up. AR and leaf nodes will not forward multicast packets.

To guarantee the semantics of multicast, the default multicast approach is suggested. However, the unidirectional multicast can be adopted to improve the transmission efficiency. In our simulations, the default multicast is assumed.

C. Global Connectivity and Mobile IPv6 Support

As aforementioned, the proposed IPv6-based MANET allows IPv6 mobile nodes in a MANET to access the global IPv6 Internet via an AR. The global IPv6 address of a mobile node is created by attaching its logical address to the

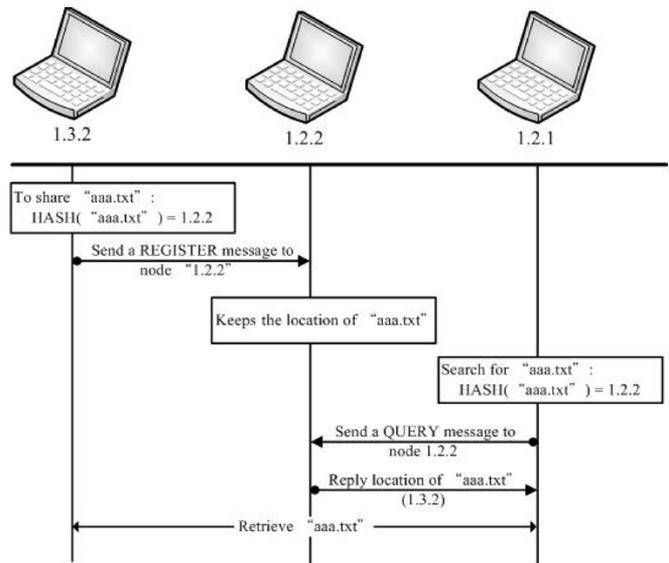
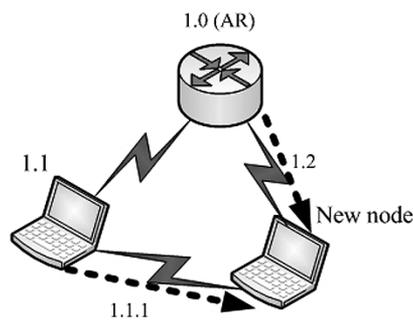


Fig. 8. Example of information sharing.

global prefix obtained from the RA message. For example, assume that the global prefix of the AR is “3ffe:302:11:1::/64”. The link local address and global address of the node with logical address “1.2.2” will be “fe80::1220:0:0:0” and “3ffe:302:11:1:1220:0:0:0”, respectively.



(a)

```

root@jacob:~/ipv6_20
檔案(F) 編輯(E) 顯示(V) 終端機(T) 移至(G) 求助(H)
1 wlan0 hw address: 00:0c:f1:17:67:9c
2 initialing.....
3 GET new available logical address= 111; nowaddr= 111
4 GET new available logical address= 12; nowaddr= 12
5 /sbin/ifconfig wlan0 add fe80::1200:0000:0000:0000/64
6 /sbin/ifconfig wlan0 add 3ffe:0302:0011:0001:1200:0000:0000:0000/64
7 /sbin/route -A inet6 add 3ffe:0302:0011:0001:1200:0000:0000:0000/68 gw
8 fe80::1000:0000:0000:0000 dev wlan0
9 /sbin/route -A inet6 add default gw fe80::1000:0000:0000:0000 dev wlan0
10 current address= 12
11 current CoA= 3ffe:0302:0011:0001:1200:0000:0000:0000

```

(b)

```

root@jacob:~/ipv6_20
檔案(F) 編輯(E) 顯示(V) 終端機(T) 移至(G) 求助(H)
1 send HEARTBEAT to 10 seq:7
2 received: HEARTBEAT_ACK from 10 seq:7
3 send HEARTBEAT to 10 seq:8
4 received: HEARTBEAT_ACK from 10 seq:8
5 send HEARTBEAT to 10 seq:9
6 received: HEARTBEAT_ACK from 10 seq:9
7 send HEARTBEAT to 10 seq:10
8 received: HEARTBEAT_ACK from 10 seq:10
9 send HEARTBEAT to 10 seq:11
10 received: HEARTBEAT_ACK from 10 seq:11
11 send HEARTBEAT to 10 seq:12
12 received: HEARTBEAT ACK from 10 seq:12

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(c)

Fig. 9. Demonstration of the JOIN and maintenance procedure. (a) Demonstrated scenario. (b) JOIN procedure. (c) Maintenance procedure.

Mobile IPv6 will be supported such that a mobile node can move from one MANET to another MANET. Mobile IPv6 includes many features to support seamless mobility, such as stateless address autoconfiguration, and neighbor discovery. The scenario of supporting Mobile IPv6 in the proposed IPv6-based MANET is shown in Fig. 7. A mobile node joins a MANET and gets a global IPv6 address at first. It then moves to another MANET where it will perform the JOIN procedure again to join the new MANET as it will find that it cannot contact with its parent node any more. After joined the new MANET, it will receive a new global prefix and form its new global IPv6 address, which will become its CoA. It can now also connect to the global IPv6 Internet. As a consequence, it can then perform the Mobile IPv6 procedures, such as send binging update to original home agent and corresponding nodes. (We assume an AR also plays the role of home agent in Fig. 7.)

D. P2P Information Sharing System on IPv6-Based MANET

As P2P applications become more and more popular, they could be the killer applications of IPv6. Therefore, in this

paper, we also design a P2P information sharing system over the proposed IPv6-based MANET based on the distributed hashing table (DHT) technique. The proposed P2P system is a distributed, but structured system. The tree structure aforementioned will be also the underlying P2P infrastructure. The logic address is also used as the node id (key) of the P2P system. To share information, a node uses the filename or some keywords as the input to a hash function. The output of the hash function, called a key, will correspond to the logic address of a mobile node which will be responsible for storing the information of the shared object. An example of the register and retrieve procedure of a shared object is shown in Fig. 8. In Fig. 8, node "1.3.2" wants to share an mp3 file with filename "aaa.txt". It first uses the hash function to obtain the node address (key) for storing the information. Assume the result of hashing is "1.2.2." Node "1.3.2" will send a REGISTER message to node "1.2.2" using its IPv6 link local address. Upon receiving the REGISTER message, node "1.2.2" will keep the mapping information of the filename and the address of the owner, which, in this case, is (1.3.2, aaa.txt). Since the node with address of

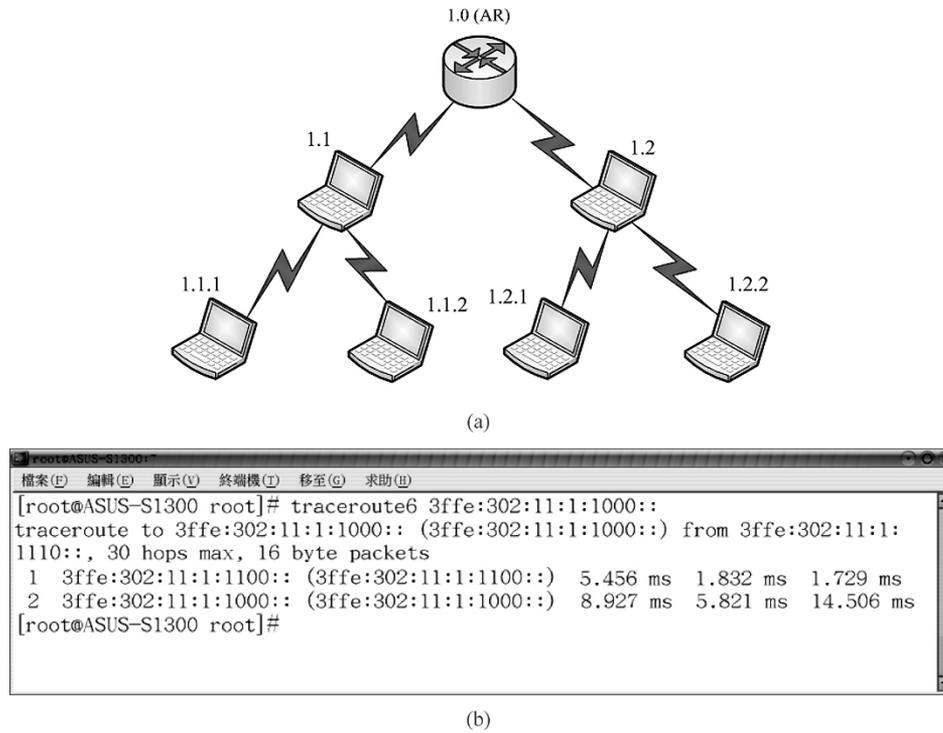


Fig. 10. Demonstration of the routing protocol from node “1.1.1” to “1.0.” (a) Demonstrated scenario. (b) Results by running traceroute from node “1.1.1” to “1.0.”

the hashing result may not exist in the network, the node that cannot further forward the REGISTER message must store this mapping information. A node searches for the “aaa.txt” file will send a QUERY message to node “1.2.2” based on the result of hash function.

III. PROTOTYPING AND IMPLEMENTATION

We will evaluate the proposed IPv6-based MANET from two aspects. In this section, we demonstrate the feasibility of the proposed protocol via prototyping a real system. In the next section, we evaluate the efficiency of the proposed protocol. Our implementation uses notebooks equipped with 802.11b wireless LAN cards. One of the notebooks is used to simulate the AR and the others act as mobile nodes. The operation system on notebooks is Redhat Linux 9.0 (kernel v2.4.22). We implemented tree overlay construction and maintenance protocols, unicast/multicast routing protocols, and the P2P information sharing system on the proposed IPv6-based MANET.

A. Implementation of Tree Overlay Maintenance Protocols

We first demonstrate the implementation of the JOIN procedure and the maintenance procedure using the scenario shown in Fig. 9(a), where a new node joins to an existing MANET with two nodes: “1.0” (AR) and “1.1.” Fig. 9(b) shows the messages received by the new node during the JOIN procedure. Specifically, lines 3 and 4 of Fig. 9(b) show that it gets logic addresses of “1.1.1” and “1.2” from node 1.1 and AR, respectively. The new node selects address “1.2” and automatically sets its link local address and global IPv6 address [Fig. 9(b) lines 5 and 6]. Lines 10 and 11 of Fig. 9(b) show the current logical and IPv6

addresses of the new node, respectively. After the new node configured its logic address and parent node, it will send heartbeat messages to its parent (node “1.0”) periodically. Fig. 9(c) shows the heartbeat messages and heartbeat acknowledges sent and received by the node.

B. Implementation of Routing Protocol

In order to ensure that the routing protocol is feasible, we used the traceroute tool to verify whether a routing path was established. The demonstrated scenario is showing in Fig. 10(a). Fig. 10(b) shows the results by running traceroute from node “1.1.1” to “1.0” which indicates that a packet from node “1.1.1” can reach node “1.0” via node “1.1.”

C. Implementation of P2P Information Sharing System

Fig. 11 shows the implementation of a P2P information sharing system. In this demonstration, a node who wants to share a text file with filename “aaa.txt” uses the hash function to obtain the target node address “1.1” (key) for storing the information first. Other nodes can then retrieve the shared file via the search and retrieve protocols.

IV. PERFORMANCE EVALUATION

In this section, we conducted our simulations using the Qualnet network simulator [19]. Our simulation models a network of 50 ~ 200 mobile nodes placed randomly within a 1000 × 1000 area. Radio propagation range for each node is 200 meters and channel capacity is 11 Mb/s. The random way point model [20] is adopted as our mobility model in which the pause time is varied from 0 to 400 s. The traffic model uses constant bit rate (CBR) source. Specifically, the simulated

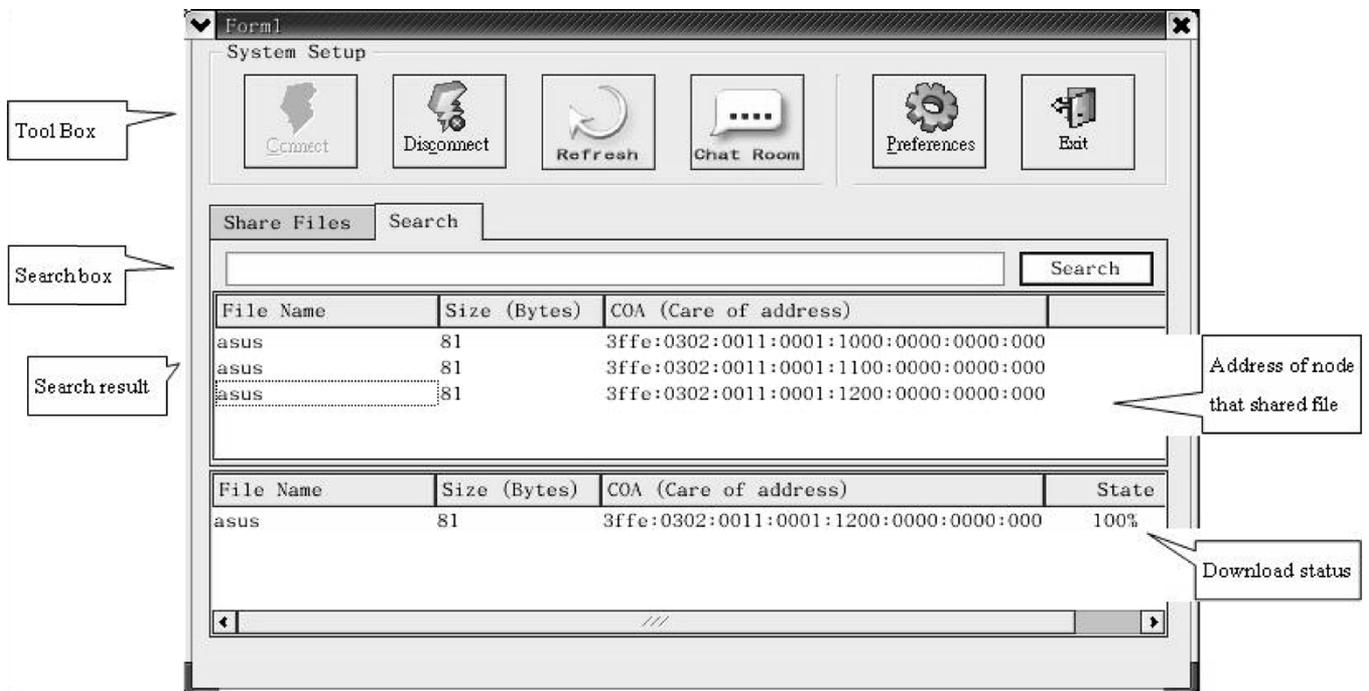


Fig. 11. P2P information sharing system based on DHT.

MANET consists of 500 CBR sources, each with sending rate of 1 packet/s and the packet size is 1024 bytes. We expect most of the traffic is to access the global Internet, so in our simulations, we also simulate the scenarios that Internet traffic contributes 80% of the traffic. Mobility speed is varied from 0 to 10 m/s. Multiple runs, each runs for 600 simulation times, are conducted for each scenario. The collected results are averaged over all runs and 95% confidence intervals are calculated.

A. Unicast Routing Protocol Results and Analysis

In this section, we compare the performance of the proposed unicast routing protocol, denoted as tree-based unicast, with that of DSDV and OLSR from different aspects. Performance metrics of interest include packet delivery ratio and number of control packets. Performance is evaluated under several scenarios, e.g., 1) various numbers of nodes; 2) various pause times; and 3) various mobility speeds, to analyze the performance of mobility effect and node density effect. The packet delivery ratio is defined as the number of data packets actually received by receivers over the number of data packets sent by sources. The number of control packets is defined as the total number of control packets generated. In our system, control packets include JOIN requests, JOIN responses, JOIN response ACKs, heartbeat messages, and heartbeat response ACKs.

Fig. 12 shows the proposed unicast routing protocol yields fewer number of control messages than OLSR, but approximates to DSDV. The proposed routing protocol performs reasonable well. Note that our routing protocol does not exchange routing information with neighbors, on demand or periodically, thus reduces a lot of routing overhead. However, frequent heartbeat messages are sent to keep tree structure as stable as possible. That is the reason that our protocol yields competitive control overhead as compared with DSDV. From Fig. 12(a), we

can observe that the increase in node number, which results in a denser topology, causes the OLSR protocol generates tremendous number of control packets. However, it only causes a linearly increase in our protocol and DSDV. Fig. 12(b) and (c) shows that the number of control messages is rather independent of the pause time and mobility for those protocols. In these two figures, we observe that OLSR yields nearly eight times more control packets as compared with our protocol because OLSR periodically issues Hello and Topology Control messages to monitor the deformation of topology constantly.

From Fig. 13, we observe that the proposed unicast routing and OLSR achieves considerably better packet delivery ratio than DSDV. Fig. 13(a) shows that our protocols, DSDV and OLSR perform comparably packet delivery ratio at lower density. As the number of nodes increase which makes the larger degree of each node, the proposed protocol is easier to form a short and wide tree. That is why our protocol performs increasingly better than both DSDV and OLSR in high-density network. Fig. 13(b) shows that the packet delivery ratio is also rather independent of number of nodes and pause time for those protocols. Fig. 13(c) shows that mobility reduces packet delivery ratio since network topology changes more frequently. Note that our protocol is designed for low mobility scenario, thus, our protocol achieves better results when mobility speed is less than 2 m/s.

From Figs. 12 and 13, we conclude that the packet delivery ratio of OLSR performs slightly better than our proposed unicast routing protocol. However, in order to achieve the better results of packet delivery ratio, OLSR yields a significant number of control packets. On the other hand, with the competitive control overhead, our protocol achieves better packet delivery ratio than DSDV. Thus, the proposed routing protocol reasonably tradeoff packet delivery ratio with control overhead.

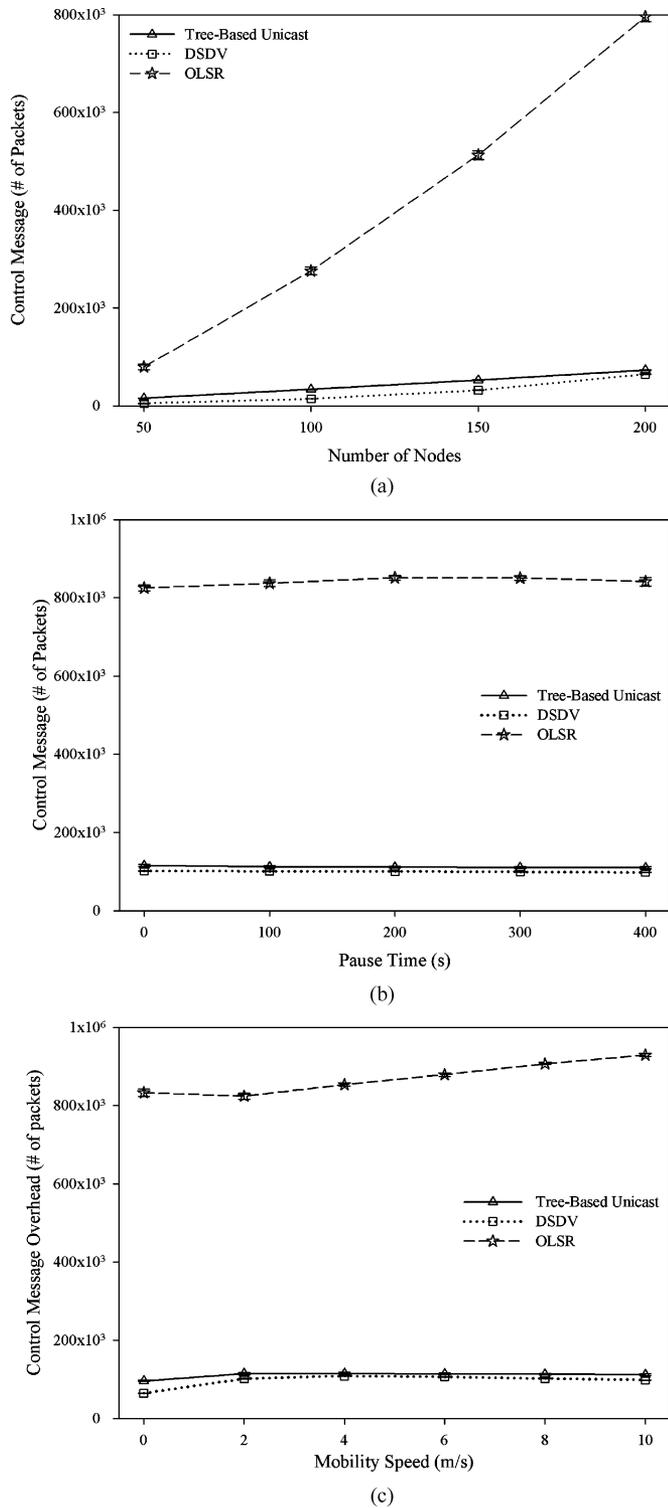


Fig. 12. Number of control packets under several scenarios. (a) Number of node. (b) Pause time. (c) Mobility speed.

B. Multicast Routing Protocol Results and Analysis

To evaluate the performance, in terms of efficiency and effectiveness, we compare the proposed multicast routing protocol, which denoted as tree-based multicast, with the flooding approach. Two metrics, total number of data packet received and packet delivery ratio, are used to evaluate the effectiveness and

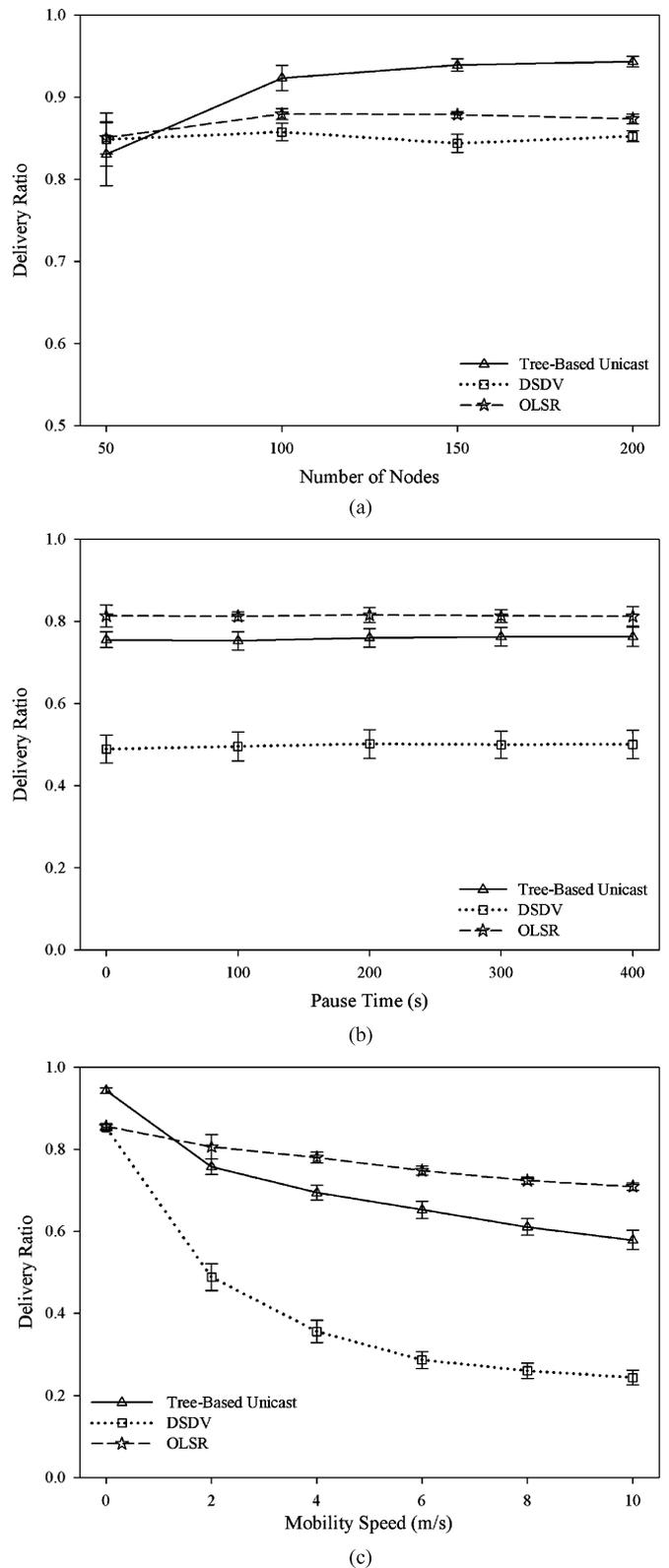


Fig. 13. Deliver ratio under several scenarios. (a) Number of node. (b) Pause time. (c) Mobility speed.

efficiency of a protocol, respectively. The efficiency of a protocol shows by number of data packets, including duplicated packets, received by all receivers. The more packets received the less efficiency of the protocol. The packet delivery ratio is

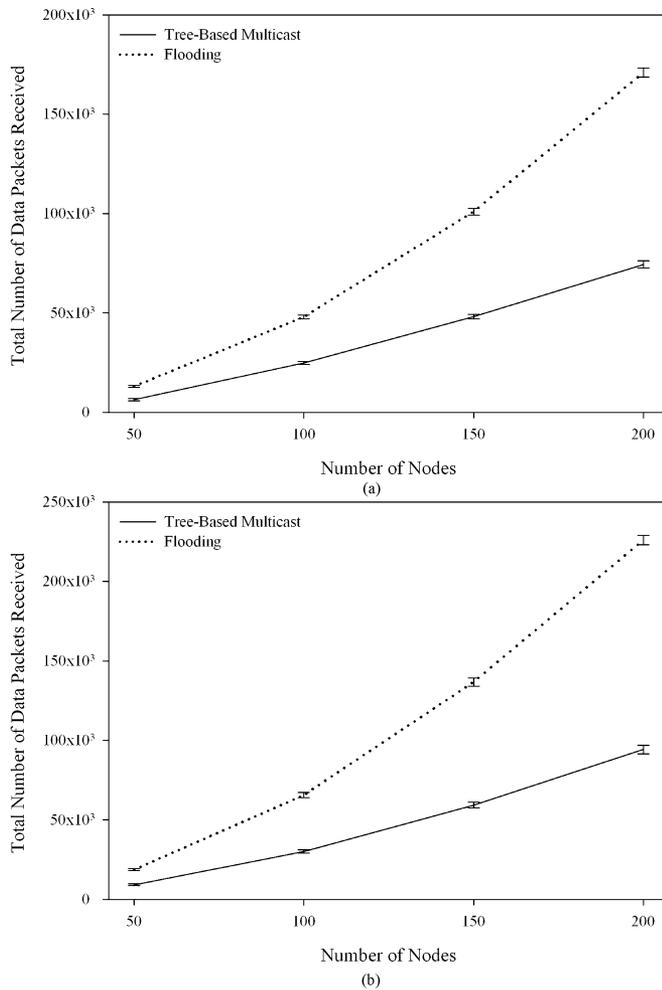


Fig. 14. Total number of data packets received under various mobility speeds. (a) Mobility speed = 0 ms. (b) Mobility speed = 2 ms.

defined as the number of nonduplicated data packets actually received by receivers over the number of packets supposed to be received by receivers.

The flooding approach simply forwards each multicast packet, received for the first time, to its neighbors. One multicast group with a single source is simulated. Fig. 14(a) and (b) shows that increase in node number results in significant increase in packets received in the flooding approach. However, the number in the tree-based multicast routing protocol is only slightly increased. We observe that multicast packets are not forwarded by leaf nodes is the major factor of this improvement. Fig. 14(a) and (b) also examines the effect of mobility on the total number of data packet received. As we can observe that both protocols are rather independent of the mobility speed and the tree-based multicast routing still outperforms the flooding approach under a network with mobile nodes. Results from Fig. 14(a) and (b) indicates that the proposed multicast routing is quite efficient and scalable.

Fig. 15(a) and (b) presents the effectiveness of protocols under various number of nodes and mobility speeds. The tree-based multicast performs comparable to flooding. Although the delivery ration is a little bit lower than that of the flooding, but more than 90% of data packets are delivered in

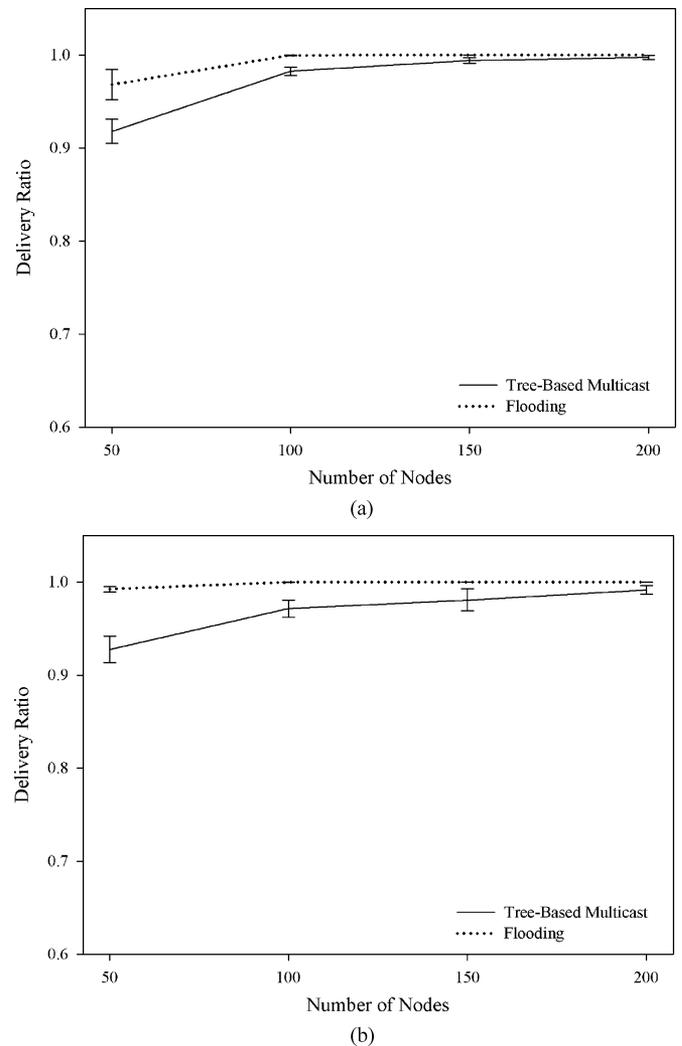


Fig. 15. Deliver ratio under various mobility speeds. (a) Mobility speed = 0 ms. (b) Mobility speed = 2 ms.

all simulations. The flooding approach performs better because that it broadcasts a lot more packets and broadcast is not reliable. This is verified by that the delivery ratio of the proposed approach approaches that of flooding as the number of network nodes increase because more packets are broadcasted.

V. CONCLUSION

In this paper, we have proposed a self-organizing, self-addressing, self-routing IPv6-based MANET, which supports global connectivity and IPv6 mobility. Unique features of our design include mobile hosts form a tree overlay automatically, self-configured logic address of a mobile host is used for IPv6 address configuration and MANET routing, efficient routing without exchanging routing information (on demand or periodically), the tree overlay also helps the development of a P2P file sharing system. Feasibility of the proposed IPv6-based MANET is demonstrated by a prototyping system. Simulation results also show the efficiency of the proposed unicast and multicast routing protocols.

Several issues of the proposed IPv6-based MANET require further study. For example, we are designing a power saving

protocol. Internet games (distributed virtual environment) over the proposed MANET are also under investigation.

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