A Cross-Layer Approach to Heterogeneous Interoperability in Wireless Mesh Networks

Shih-Hao Shen[1], Jen-Wen Ding[2], Yueh-Min Huang[1]

[1]Department of Engineering Science National Cheng Kung University, Tainan 701, Taiwan, R.O.C.
{n9892110, huang}@{ccmail, mail}.ncku.edu.tw
[2]Department of Information Management, National Kaohsiung University of Applied Sciences,
Kaohsiung 807, Taiwan, R.O.C.
jwding@cc.kuas.edu.tw

Abstract. Routing in a wireless mesh network is a heterogeneous interoperability problem. First, it is possible that some users may disable the relaying functions of their mobile devices in order to save the computing power and battery charge. This will results in heterogeneous relaying capabilities. Second, due to the absence of standard layer-3 ad-hoc routing protocols, various devices may employ different layer-3 routing protocols, making routing difficult. A trivial solution to the above two problem is to flood packets through the un-routable regions to reach the destination region. However, flooding is a brute force approach and will make a broadcast storm, resulting in low throughput of the whole network. In this paper, we propose a cross-layer approach to solve the above problem. Our analysis results show that the proposed cross-layer approach can efficiently provide interoperability without causing broadcast storm.

1 Introduction

There has been a big interest in commercial wireless mesh networks in the recent past. Wireless mesh networks [1] and [2] are ad hoc wireless networks formed to provide an alternate communication infrastructure for mobile and fixed users, in addition to cellular networks. Compared to traditional infrastructure-based networks, wireless mesh networks can be easily deployed and the topology can be easily and rapidly changed via self-organization. Hence wireless mesh networks provide the most economical data transfer capability with support for user mobility [8] and [9]. Many wireless mesh networks have been installed around the world. For example, Nortel networks wireless mesh network solution has been adopted in Taipei city to offer highly scalable, cost-effective last-mile communication to end users [12]. Figure 1 shows the architecture of a wireless mesh network.

Heterogeneous interoperability in a commercial wireless mesh network is an important design issue necessary to be addressed for two reasons. First, since relaying takes up nodes' resources such as computing power and battery charge, some users may disable the forwarding functions of their mobile devices, and by doing so we cannot ensure a fully connected network even with high node density. Research has developed numerous layer-3 routing protocols for ad hoc wireless networks [5], [7], [10] and [11]. Though these protocols find efficient routing path for mobile nodes with minimum control overhead, most of them assume homogeneity of mobile nodes, i.e., all nodes support the full functions of a certain layer 3 routing protocol. This, however, is not the case in a commercial wireless mesh network, where some nodes may disable the relaying functions. In practice, the mobile nodes are classified into two types, the ones enabling the relaying functions and the ones disabling the relaying functions. The second reason is that due to the absence of standard layer-3 routing protocols, various devices may employ different layer-3 routing protocols.

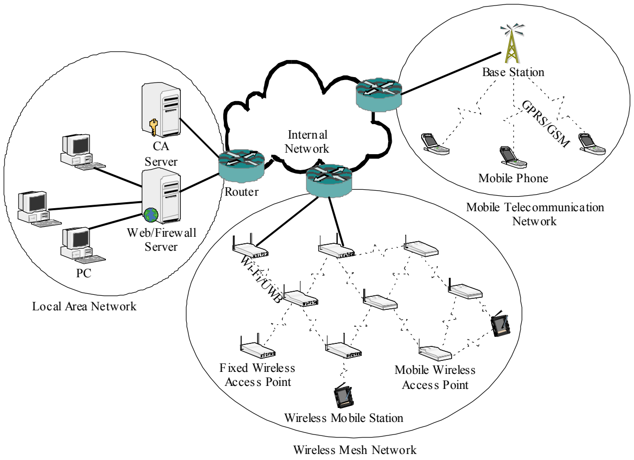


Fig. 1. Architecture of wireless mesh network [8]

Because of the two reasons mentioned above, the whole wireless mesh network can thus be partitioned into many small geographically separated regions belonging to one of the two types. In this paper, the nodes disabling the forwarding function are referred to as un-routable nodes. The nodes using different layer-3 routing protocols are also un-routable nodes for each other. The regions consisting of un-routable nodes are referred to as un-routable regions. It is noted that a region cannot communicate with its un-routable neighbor regions via layer-3 routing.

There are three type of approaches to solving the problem of un-routable regions, (1) the dual stack approach, (2) the naive layer-2 broadcast approach and (3) the cross-layer approach. The dual stack approach employs devices that support more than two protocols and act as a bridge to transform protocols. However, this approach is costly and impractical because of the limited computing power of most mobile devices. The naive layer-2 broadcast approach floods packets through the un-routable regions to reach the destination region. However, flooding is a brute force approach because it implicates the inability to acquire the whole regional topology of un-routable area. For example, node *d* is a source and node *k* is the destination as shown in Figure 2a. The optimal solution is path *d-c-e-h-k*. Both of the two are routable nodes but separated apart from un-routable regions. Thus, source node (*d*) has no choice but to flood frames. The flooding approach results too many meaningless messages at the MAC layer. As figure 2b illustrated flooding is a very inefficient scheme.

In this paper, we propose a cross-layer approach which consists of a slightly modified version of a common layer-2 protocol, DFWMAC, and a light-weight layer-3 protocol that can cooperate with various layer-3 routing protocols so as to allow the packets to be forwarded without causing a layer-2 broadcast storm. We organize the paper as follows: Section 2 describing related work and providing preliminaries, Section 3 detailing our proposed cross-layer protocol, Section 4 presenting the simulation results, and finally, Section 5 concluding.

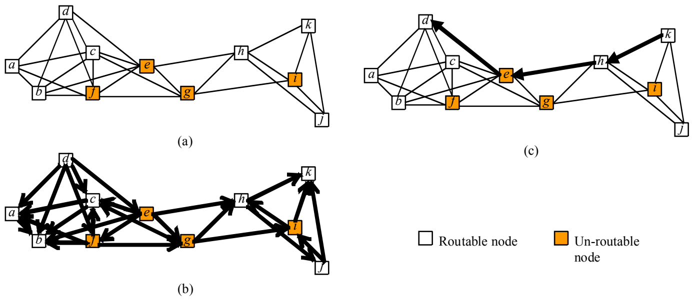


Fig. 2. Using flooding scheme to go through un-routable regions from node *d* to *k*. (a) Connection diagram. (b) Node *d* broadcasting a *search* command. (c) Node *k* responding to a *connect* command.

2 Preliminaries

In this paper, we assume that users have a common MAC layer protocol. In the recent past, numerous MAC protocols have been proposed for ad hoc wireless networks, such as MARCH[13], D-PRMA[4] and DPS[6]. Some of them can even provide guaranteed QoS delivery, such as D-PRMA, DPS. For the sake of compatibility, the proposed cross-layer approach adopts and slightly modifies DFWMAC (Distributed Foundation Wireless Medium Access Control) [3] as its MAC protocol, the DLC (distributed link conjunction) protocol. DFWMAC is the MAC protocol used in IEEE 802.11 recommended standard for wireless ad-hoc and infrastructure LANs. In this section, we briefly review the main operations of DFWMAC that are relevant to our proposed scheme.

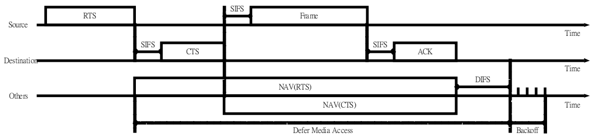


Fig. 3. RTS/CTS access mechanism in DCF

In DFWMAC, Carrier Sense Multiple Access with Collision-Avoidance (CSMA/CA) is used to combat the hidden terminal problem. The MAC coordination function is based on the distributed coordination function (DCF) in ad hoc mode, which utilizes CSMA/CA. CSMA/CA takes advantage of request-to-send (RTS) and clear-to-send (CTS). DCF is a four-way sender-initiated protocol and the most popular collision-avoidance scheme between a pair of sender and receiver. Before source node will send that check medium idle or busy. If medium was busy then use orderly exponential backoff algorithm to avoid collision. Four-way sender-initiated protocol is termed RTS-CTS-DATA-ACK or DFWMAC. As Figure 3 shown, a source node sends a RTS to a destination node. Receiving the RTS, the destination node sends back a CTS. After receiving the CTS, the source node then sends a DATA to destination node, which sends back a ACK. After the process, entry backoff window, any ready sending node contends time slots of backoff.

3 CROSS-LAYER PROTOCOL

The proposed cross-layer protocol consists of two schemes, the DLC (distributed link conjunction) scheme and the GEER (group entry and exit register) scheme. DLC slightly modifies DFWMAC, the MAC protocol used in IEEE 802.11 recommended standard for wireless ad-hoc and infrastructure LANs.

3.1 Distributed Link Conjunction (DLC) Scheme

As mentioned earlier, in the naive layer-2 approach, link connectivity from a routable region to a destination region via un-routable regions can be achieved by performing flooding in DFWMAC. As shown in Figure 2c, node *d* is a source and node *k* is the destination. Both node *d* and *k* are routable nodes but separated apart from un-routable regions. Source node just simply floods frames. The optimal solution is path *d-c-e-h-k*.

For the sake of compatibility, we design DLC by adopting and slightly modifying the well analyzed and verified MAC protocol used in ad hoc networks, DFWMAC. As shown in Figure 4, DLC uses the same basic RTS-CTS-DATA-ACK frame exchange mechanism. DLC uses piggybacked information onto RTS-CTS handshake and DATA-ACK. The piggybacked information includes (1) source routing address, (2) destination routing address, (3) a down/up stream indication bit.

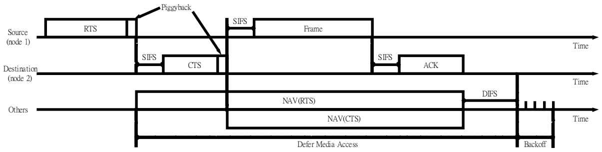


Fig. 4. Piggybacking on DFWMAC

Before data transmission, the sender transmits a *link discovery frame* using the RTS-CTS-DATA-ACK frame exchange mechanism. This link discovery frame will be flooded into the un-routable regions using broadcast (by setting the destination field as a broadcast address). All mobile nodes in the un-routable regions receiving the piggybacked information will perform three operations: (1) rebroadcast the link discovery frame, (2) temporarily cache the information, (3) starts a timer. By checking the cache, redundant link discovery frames received by a node will be discarded. The cache maintains four fields for a link discovery frame: (1) source routing address, (2) destination routing address, (3) a down/up stream indication bit, and (4) the MAC address of the previous sending node of the link discovery frame. Because of the multiple paths, the destination node may receive multiple link discovery frames, but it only acknowledges a *link confirmation frame* for the first received link discovery frame (the first received frame usually implies a shorter path). The link confirmation frame carries information similar to that carried in the link discovery frame. The link confirmation frame is then sent back to the sender node, via the reverse route that the first received link discovery frame uses, in a hop-to-hop unicast fashion to avoid broadcast storm. The intermediate un-routable nodes on the reverse path will also cache the information carried in link confirmation frame. A node receiving link discovery frame but not receiving the corresponding link confirmation frame will delete the cache information after the previously set timer is matured. The MAC layer protocol is presented in table 1.

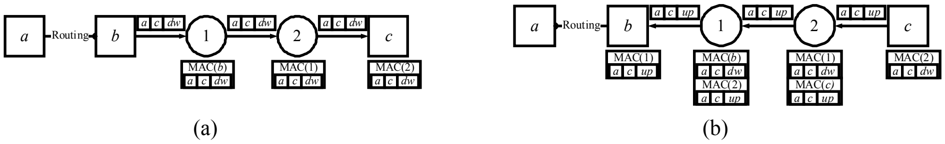
Table 1. The MAC layer protocol

```
DLC Algorithm: (Working on layer-2)
Signature:
Input:                                        Output:
  $receive(frame_j)_{j,i}, j \in nbrs$          $Send(frame_i)_{i,k}, k \in nbrs$

State:
A piggyback $p := (IP_{source}, IP_{distination}, state=\{req|rep\})$
For every $1 \leqq i \leqq n$, $n \in \{$nodes disabled layer-3 functions$\}$
  $Node_i$ create a set $C_i$
  $C_i := \phi$
An element of $C_i$ is $e := (p, MAC_{downlink}, MAC_{uplink})$
Tasks:
Periodically maintains $C_i$ by Least-Recently-Used (LRU) replacement strategy.
Overhear neighborhood rebroadcast lead to link state finish.

Transitions:
$receive(frame_j)_{j,i}$
  Effect:
    if $\exists frame_j.p \in C_i^{\{p\}}$ then
      discard $frame_j$
    else
      if $\exists frame_j.p_{state=rep} \in C_i^{\{pstate=req\}}$ then
        $send(frame_j)_{i,\ downlink}$
        $MAC_{uplink} := j$
      else
        $send(frame_j)_{i,\ null} \equiv broadcast(frame_j)_{i,\ \forall k}$
        $MAC_{downlink} := j$
$send(frame_i)_{i,k}$
  Effect:
    if $k == null$ then
      $broadcast(frame_i)$
    else
      $unicast(frame_i)_k$
```

Figure 5 shows a simple example of node *a* communicating to node *b*. Nodes *a*, *b* and *c* are routable nodes. Node *1* and *2* are un-routable nodes. Nodes *a* and *b* communicate via layer-3 routing protocol. Nodes *b* and *c* communicate by DLC. Figure 5a shows how link discovery frame is broadcasted and how intermediate un-routable nodes cache the information carried in the link discovery frame. Figure 5b shows how link confirmation frame is unicasted to the sender node via the reverse path and how intermediate un-routable nodes cache the information carried in the link discovery frame.



(a)

(b)

Fig. 5. Example of a caching frame to reserve paths.

3.2 GEER Routing Protocol

In the recent past, numerous routing protocols have been proposed for ad hoc wireless networks, such as DSDV[10], WRP[7], DSR[5] and AODV[11]. As mentioned earlier, these protocols cannot solve the interoperability problem. We consider a scenario where heterogeneous nodes are un-routable for each other because some of them may disable the forwarding functions or because they may employ different routing protocols, as shown in Figure 2a. The network is therefore partitioned into many small geographically separated regions. In a routable region, a packet can be directly sent any other node in the same region using a common layer-3 routing protocol, such as DSR or AODV. However, when a packet is sent to a destination that is in an un-routable region, a special design will be required.

Our proposed cross-layer approach employs DLC with very limited broadcast to pass packets through an un-routable region. However, two problems may arise if only DLC is used. First, the layer-2 link discovery frame of DLC may result in a routing cycle. Second, when a packet must travel through several routable and un-routable regions, in order to efficiently relay packets in a routable region without flooding, each region must perform smart relaying. The two problems are illustrated in Figure 6. To cope with the two problems, the proposed cross-layer approach uses a light-weight layer-3 routing protocol, Group Entry and Exit Register (GEER), that can cooperate with existing routing protocols for ad hoc wireless networks, such as DSR and AODV.

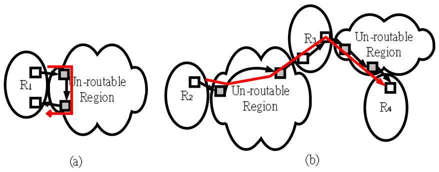


Fig. 6. Effect of routing on wireless mesh network interoperability: (a) Routing cycle. (b) Multi-regions forwarding.

In GEER protocol, three types of nodes are introduced. To prevent routing cycle and to help crossing multi-regions routing we need a node to record the entry and exit of link discovery frame of DLC. The special node is termed *GEER node*. GEER is elected from a group of nodes. To concatenate different routable regions via DLC, the nodes, termed *dam nodes*, sit between a routable and an un-routable region must perform the relaying function. A special un-routable node whose routable neighbors are in the same routable region is referred to as *surrounded node*.

The algorithm is to determine whether the node is GEER by searching a maximum degree node in a region. It is easier when routing protocol is pre-active. Dam nodes and surrounded nodes are determined as follows table 2. Every node (routable or un-routable) stores the MAC address of adjacent un-routable nodes. The GEER of a routable region keeps a GURID (Group Un-routable Identifier) table, which records the MAC and IP addresses of each routable node in the region and the MAC addresses of these nodes' adjacent un-routable nodes. If a routable node wants to detect if an adjacent un-routable node is a surrounded un-routable node, it sends a query with the MAC address of the un-routable node to GEER. If the query of GURID table shows that the un-routable node is adjacent to all routable nodes, then it is a surrounded node. A routable node can query the GEER to determine if it is a dam node by sending the MAC addresses of its adjacent nodes. If not all adjacent nodes are surrounded nodes, this routable node is a dam node. As shown in Figure 7, nodes *h*, *k*, and *j* are routable nodes and nodes *e*, *g* and *i* are un-routable nodes. Node *i* is a surrounded un-routable node because all node *i*'s adjacent MAC addresses appear in the GURID. Nodes *h* is a dam node because it is adjacent to out-region nodes *e* and *g*.

Table 2. DAM algorithm

```
DAM Algorithm: (Working between layer-2 and layer-3)
Signature:
Input:                                                  Output:
  $receive(packet_j)_{j,i}$, $j \in Homo\text{-}Network$     $Send(packet_i)_{i,k}$, $k \in Homo\text{-}Network$
State:
Broadcast storm avoidance set $A := \emptyset$
Tasks:
Precondition:
  For every n $\in H_i$, determine adapting to a dam node
  Nodes of homo-group $H_i$ elect a $GEER_i$.
Effect:
  Periodically deletes timeout element of $A$.
  $\forall$Destination $j \in H_i$, $send(packet_i)_{i,j}$
  $\forall$Destination $k \notin H_i$, $send(Send\ (packet_i)_{i,k})_{i,GEERi}$

Transitions:
$send(packet_i)_{i,k}$
  Effect:
    $send(packet_i)_{i,k}$

$receive(packet_s)_{j,i}$, s is source node
Effect:
  if $packet_s$ == GEERtoDam then
    DLC.send()
    if $packet_s \in cmd$ then
      For every $d \in D_i$
        $send(GEERtoDam(packet_s \cup \{IP_{GEERi}\}))_{i,d}$
      $A := A \cup \{ packet_s + t \}$, t is a timestamp
    else
      Run original routing protocol
  else $s \notin H_i$
    if $packet_s \in cmd$ then
      if i is distination then
        $send(GEERtoDam(rep\_packet_i))_{i,j}$
      else i is not distination
        For every $d \in D_i$
          $send(GEERtoDam(packet_s \cup \{IP_{GEERi}\}))_{i,d}$
        $A := A \cup \{ packet_s + t \}$, t is a timestamp
    else $packet_s \notin cmd$
      $send(GEERtoDam(rep\_packet_i))_{i,j}$
```

Table 3. GEER algorithm.

```
GEER Algorithm: (Working on layer-3)
Signature:
Input:                                                  Output:
  $receive(packet_j)_{j,i}$, $j \in Homo\text{-}Network$     $Send(packet_i)_{i,k}$, $k \in Homo\text{-}Network$
State:
Broadcast storm avoidance set $A := \emptyset$
Command set cmd={"Send", "GEERtoDam"}
Tasks:
Precondition:
  For every n $\in H_i$, determine adapting to a dam node
  Nodes of homo-group $H_i$ elect a $GEER_i$.
Effect:
  Periodically deletes timeout element of $A$.
  $\forall$Destination $j \in H_i$, $send(packet_i)_{i,j}$
  $\forall$Destination $k \notin H_i$, $send(Send\ (packet_i)_{i,k})_{i,GEERi}$

Transitions:
$send(packet_i)_{i,k}$
  Effect:
    $send(packet_i)_{i,k}$

$receive(packet_s)_{j,i}$, s is source node
  Effect:
    if $s \in H_i$ then
      if $packet_s \in cmd$ then
        For every $d \in D_i$
          $send(GEERtoDam(packet_s \cup \{IP_{GEERi}\}))_{i,d}$
        $A := A \cup \{ packet_s + t \}$, t is a timestamp
      else
        Run original routing protocol
    else $s \notin H_i$
      if $packet_s \in cmd$ then
        if i is distination then
          $send(GEERtoDam(rep\_packet_i))_{i,j}$
      else i is not distination
        For every $d \in D_i$
          $send(GEERtoDam(packet_s \cup \{IP_{GEERi}\}))_{i,d}$
        $A := A \cup \{(packet_s, t)\}$, t is a timestamp
```

We then discuss the concept of GEER routing algorithm shown in Table 3. GEER is a centralized control in each routable region. Every packet sent out and sent in the region needs to register to GEER. By storing and comparing packets to see if it is repeatedly received, GEER can avoid a routing cycle mentioned earlier. If a destination node does not exist in the region, GEER forwards packets to its dam nodes to go through un-routable regions to the destination node. As shown in Figure 7, consider a simplified example that node *d* needs to communicate to node *k*. Initially, node *d* sends a *GEER routing query* to *c*. Because node *k* does not exist in *c*'s region, such as *c* multicasts the query to its dam nodes *c* and *d* to go through un-routable region. In the first path, a routing cycle *c*-*e*-*d* occurs. When *d* receives a frame with piggyback, it obtains the destination identifier and queries it by GEER *c*. The GEER finds it is a redundant query packet and then returns the command of "discard" to *d*. In the second path, *c*-*e*-*h*-*k*, when receiving a frame with piggyback, *k* obtains the destination identifier and queries it by GEER *e*.

It is noted that the proposed cross-layer scheme can cooperate with other nodes not supporting GEER and therefore maintains interoperability in wireless mesh network as Figure 7 shown. There is at least one node that supports GEER, however. Otherwise, there might be some independent regions that impede routing.

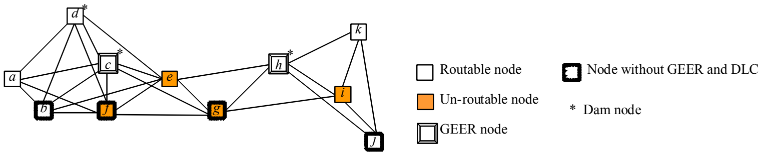


Fig. 7. A GEER operating snapshot in figure 2, where partial network lacks GEER and DLC operation.

4 Performance Evaluation

In order to verify the cross-layer protocol, we conduct a series of simulations using the Distribution Wireless Mesh Network Simulator developed by ourselves. We first investigate how heterogeneous nodes will be distributed over an area. We perform a set of simulations for heterogeneous node distribution, which ranges from 50 to 450 nodes (with increase of 50) spreading randomly in a network area of 1500×1500 meter^2. We use random distribution on two-dimension space. To take into account the fact that mobility may affect linking topology, we assume that renew process happens prior to rush hour everyday. We simulate different density of routable nodes' from the snapshots as renew and ignore mobility.

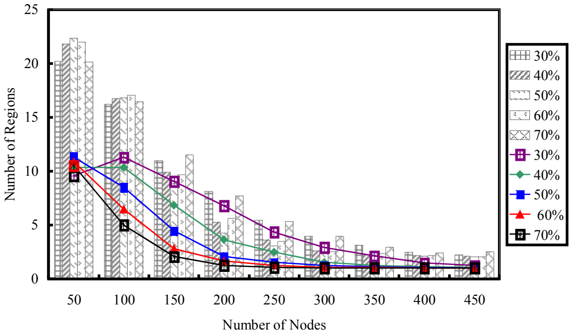
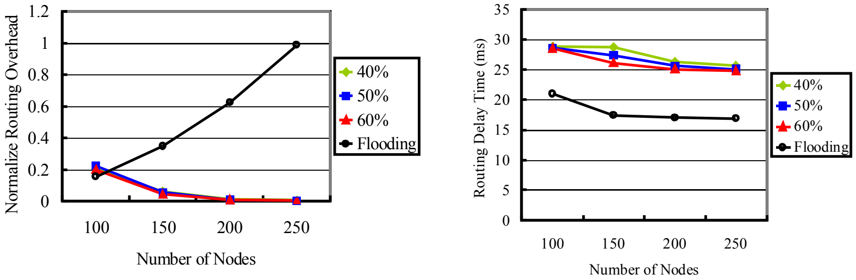


Fig. 8. Heterogeneous case – when the density of routable nodes are 30%, 40%, 50%, 60% and 70%: Average number of routable regions (frequency polygon) and average number of total regions (histogram)

We study the effect of the ratios of nodes with and without cross-layer protocol on connection regions. In this experiment, the simulated topology consists of only two types of nodes, routable and un-routable nodes. As we can observe from the simulation result shown in Figure 8, what mainly affects the amount of routable regions is the number of routable nodes. The number of routable nodes is over 150 in the set environment, and this almost leads to a complete routable region. Hence we set the parameters for the cross-layer protocol as follows: the densities of routable nodes are 40%, 50%, and 60%, and the total numbers of nodes are 100, 150, 200, and 250, respectively. We evaluate overhead of routing control, and the result is given in Figure 9a. The result shows that, when we use flooding to reach destination nodes, the amount of control packets dramatically increases with the increasing numbers of nodes. In our cross-layer protocol, most of the control packets come from the first time discovery. Given a certain amount of routable nodes in the environment, however, it takes much fewer control traffic overhead to complete routing when our cross-layer protocol is used. Next, we investigate the routing delay time and the result is given in Figure 9b. Our cross-layer approach does not perform better than the simple layer-2 flooding approach because it takes more time to perform the layer-3 algorithm. However, we can observe figure 9 that the cross-layer protocol is more beneficial because the number from source to destination takes only 4 hops in our simulation environment.

Table 4. Simulation parameters

Network area size	1500x1500 m^2
Transmission radius	225 m
Transmission Rate	11 Mbps
Avg. frame size	64 bytes
Avg. packet size	512 bytes
Avg. Routing discovery	3 (normal distribution, standard deviation: 3)
Speed	0~1.41 m/s (random walk)
Simulation Time	300 Sec



(a) (b)

Fig. 9. Heterogeneous case - 40%, 50% and 60% routable nodes: (a) Normalized routing overhead vs. number of total nodes. (b) Route discovery delay vs. number of total nodes

5 Conclusion

In a commercial wireless mesh network, interoperability among heterogeneous mobile devices is a difficult design issue. Firstly, it is possible that some users may disable the relaying functions of their mobile devices to save the computing power and battery charge. This phenomenon results in heterogeneous relaying capabilities. Secondly, due to the absence of standard layer-3 routing protocols, various devices may employ different layer-3 routing protocols. A naive approach to the interoperability problem is to flood traffic through un-routable regions via a common MAC protocol. However, this will result in a broadcast storm, yielding a low throughput of the whole network. In this paper, we propose a cross-layer approach to addressing this problem. The cross-layer protocol consists of two key components: (a) DLC, a MAC protocol that effectively restrains the broadcast storm occurring in the un-routable regions, (b) GEER, a light-weight routing protocol that uses Group Entry and Exit Register node to avoid routing cycles and to help multi-region relaying. It is worth mentioning that DLC is a slightly modified version of DFWMAC, the MAC protocol used in IEEE 802.11 recommended standard for wireless ad-hoc networks and infrastructure LANs. Our analysis results show that the proposed cross-layer approach can achieve the interoperability goal without causing the broadcast storm problem.

Reference

1. Akyildiz, I.F., Wang, X. and Wang, W.: Wireless Mesh Networks: A Survey. Computer Networks Journal, Vol. 47, 3 (2005) 445-487
2. Ashish, R., Kartik, G. and Chiueh, T. C.: Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks. ACM SIGMOBILE Mobile Computing and Communications Review Vol. 8, Issue 2, 4 (2004)
3. IEEE Computer Society: 802.11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. 7 (1997)
4. Jiang, S., Rao, J., He, D., Ling, X. and Ko, C.C.: A simple distributed PRMA for MANETs. IEEE Trans. Veh. Tech., Vol.51, No.2, 3 (2002) 293-305
5. Johnson, D. B. and Maltz, D. A.: Dynamic Source Routing in Ad-Hoc Wireless Networks. Mobile Computing, 1994.
6. Kanodia, V., Li, C., Sabharwal, A., Sadeghi, B. and Knightly, E.: Distributed multi-hop scheduling and medium access with delay and throughput constraints. ACM/Baltzer Journal of Wireless Networks, Vol. 8, No. 5, 9 (2002) 455-466
7. Murthy, S. and Garcia-Luna-Aceves, J. J. :An Efficient Routing Protocol for Wireless Networks. MONET, Vol.1, No. 2, 10 (1996) 183-197
8. Nortel Networks Corp.: Wireless Mesh Network Solution. http://www.nortelnetworks.com/solutions/wrlsmesh/#, (2005)
9. Oreilly Corp.: Wireless Mesh Networking. http://www.oreillynet.com/pub/a/wireless/2004/01/22/wirelessmesh.html, 1 (2001)
10. Perkins, C. E. and Bhagwat, P.: Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers. Comp. Commun. Rev., 10 (1994) 234–244
11. Perkins, C. E. and Royer, E. M.: Ad-Hoc On-Demand Distance Vector Routing. In Proc. 2nd IEEE Wksp. Mobile Comp. Sys. and Apps., 2 (1999) 90–100
12. Toh, C. K., Vassiliou, V., Guichal, G. and Shih, C. H.: MARCH: A medium Access Control Protocol for Multi-Hop Wireless Ad Hoc Networks. Proc. of IEEE MILCOM'00, Vol. 1, 10 (2000) 512-516