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A SURVEY OF INTEGRATING IP MOBILITY PROTOCOLS AND MOBILE AD HOC NETWORKS

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ABSTRACT

A mobile ad hoc network (MANET) is an infrastructureless, autonomous, and standalone network. A MANET can be flexibly and simply deployed in almost any environment, but it has limited wireless coverage and its connectivity is limited to the MANET boundary. The growth of the Internet and its services and applications — and the trend in the fourth generation (4G) wireless networks toward All-IP networks — have led to an increasing demand for enabling MANET nodes to connect to the Internet and use its services and applications. Mobile IP and IP micromobility protocols enable a mobile node to access the Internet and change its access point without losing the connection. The mobile node should be in the coverage range of the access point and should have a direct connection to it. So, with the cooperation between MANET routing protocols and the IP mobility protocol, Internet connectivity to MANET nodes can be achieved. Many solutions have been proposed to enable MANETs to connect to the Internet using IP mobility protocols. This article presents a survey of solutions for integrating MANETs with the Internet, with the intent of serving as a quick reference to current research proposals for Internet connectivity for mobile ad hoc networks based on IP mobility protocols. A qualitative comparison of the routing solutions for integration is presented. The limitations of these integration solutions are also investigated. A framework for integrating the Cellular IP access network and MANETs is introduced. This survey concludes with further points for investigation.

The growth of the Internet and its services and applications, and the convergence towards All-IP networks in fourth generation (4G) wireless networks, where all traffic (data, control, voice and video services, etc.) will be transported in IP packets, has led to an increasing demand for mobile wireless access to Internet services and applications. Wireless networks can be divided into two types: network with infrastructure (i.e., network with base stations and centralized administration) and network without infrastructure (i.e., ad hoc networks).

Mobile IP [1, 2] is the current standard for supporting IP mobility of mobile nodes in the wireless networks with infrastructure. Mobile IP enables the mobile node to access Internet and changes its access point without losing the connection. The mobile node should be in the coverage range of Mobile IP base station (access point) and has a direct connection to it. Therefore, Mobile IP can maintain the connection to the mobile nodes, which are within its base station's coverage range. Mobile IP suffers from many drawbacks [3–5], such as high handoff delay, which results in a high number of packet loss, especially in the case of frequent handoff (within the domain), since the foreign agent (FA) must inform the home agent (HA) about the new IP Care-of-Address (CoA) after each handoff. Many solutions have been developed to efficiently support local mobility inside IP wireless networks such as Cellular IP [6–8], Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [9, 10], and Hierarchical Mobile IP (HMIP) [11], which are called IP Micro-mobility protocols.

MANET [12, 13] is a kind of wireless network architecture that can be flexibly deployed in almost any environment (e.g., conference rooms, forests, battlefields, etc.) without the need of network infrastructure or centralized administration. Each node in a MANET serves as a router and performs mobility functionalities in an autonomous manner. The drawbacks of MANETs are limited bandwidth and battery power, limited wireless coverage, a limited number of services and applications, and dynamic network topology.

Integration of MANETs to the fixed infrastructure IP access network has many usage scenarios, and it provides many advantages for both Infrastructure and MANET networks together. MANET users can access the Internet and access a wide range of Internet services and applications. Because of the limited coverage of MANETs, integration of MANETs with the fixed infrastructure IP access network can increase this coverage. Integration of MANETs with the fixed infrastructure IP access network based on IP mobility protocols enables MANET nodes movement between different MANETs without losing the connection. It can provide mobility support between different nonoverlapping and overlapping MANETs with multiple gateways. The fixed Infrastructure network can be extended to include the dead zone and cover long areas beyond the range of fixed cellular infrastructure. The number of access points can also be decreased.

This article presents a survey of the integration solutions for MANETs with regard to the Internet, with the intent of serving as a quick reference for current research issues in Internet connectivity to mobile ad hoc networks based on Mobile IP and IP micro-mobility protocols. A comparison of the solutions for integrating MANETs with the Internet is presented.

The rest of the article is divided into seven sections. In the next section, a detailed description of IP mobility management protocols is presented. These protocols are classified into two categories: IP macro-mobility protocols and IP micro-mobility protocols. Examples of the first category such as Mobile IPv4 and Mobile IPv6 are described. Examples of the second category such as Cellular IP, HAWAII, HMIP and others are also described. Then we present a description of mobile ad hoc routing protocols. These protocols are classified into two main categories: table driven routing protocols and ad hoc on-demand routing protocols. Two examples of the first category, which are DSDV and OLSR, are described. One example of the second category, called AODV, is also described. Next we present an overview of 13 different integrated routing solutions. Most of these integration solutions are based on Mobile IP and some of these solutions intend to support micro-mobility. A comparison of these integration solutions is presented. We describe a framework for integrating the Cellular IP Access Network and MANETs. Finally, we conclude our article.

IP Mobility Management Protocols

IP mobility management protocols are used to manage node mobility between different subnets inside the domain or between different domains. IP mobility management protocols can be classified into two main groups: IP macro-mobility protocols and IP micro-mobility protocols. A comprehensive survey for IP mobility management can be found in [14–18]. In this section we describe the IP mobility protocols, which can be used for integrating MANETs with the Internet and providing IP mobility support to the mobile nodes.

IP Macro-Mobility Protocols

Macro-mobility is the movement (roaming) of mobile nodes between two subnets (or cells) in two different domains. IP macro-mobility protocols are designed to handle the mobile node movement between two domains without disconnection. One of the characteristics of IP macro-mobility protocols is that these protocols cooperate with IP routing mechanisms to integrate fixed and mobile networks. The most known standard for IP mobility support is Mobile IP [1], which is the best and the most frequently adopted solution for supporting IP macro-mobility. It is proposed by IETF to enable the mobile node to access Internet and roam freely between different subnets without losing the connection. Mobile IP has two versions, Mobile IPv4 and Mobile IPv6. Mobile IPv4 [2] is the current standard for supporting IPv4 nodes mobility in the IPv4 networks. The Mobile IPv4 network architecture includes three new functional entities:

- Mobile node (MN): A host or router, which changes its access point from one subnet to another without changing its home IP address.
- Home agent (HA): A router located on a mobile node home network.
- Foreign agent (FA): A router located in each foreign network, which can enable the mobile node to access Internet.

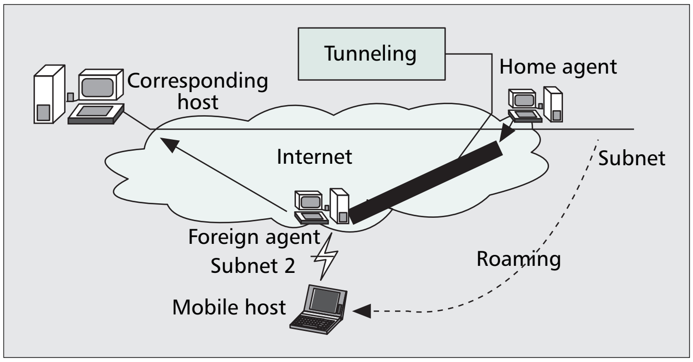
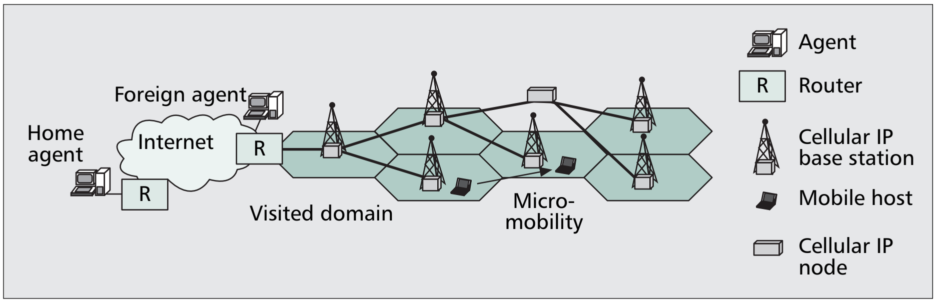


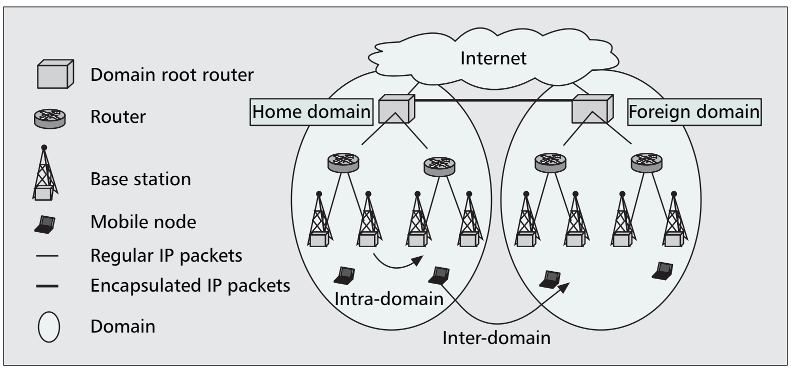
Figure 1. *Mobile IPv4 architecture.*

Figure 1 illustrates the architecture of Mobile IPv4 and shows mobile node movement from subnet 1 to subnet 2. It also shows packets routing (triangle routing) in this architecture. The HA and the FA periodically send an agent advertisement message. When the mobile node receives an agent advertisement message, it can detect whether or not it has moved to new subnet. The mobile node can also discover new agent by soliciting an agent advertisement message through sending an agent solicitation message. Mobile nodes use three movement detection mechanisms [1, 2] to initiate the handoff to the new subnet: Eager Cell Switching (ECS), Lazy Cell Switching (LCS), and Prefix Matching (PM), when a mobile node detect that it has moved to new mobility Agent, it acquires a CoA on the new foreign network using either a CoA of the Foreign Agent (FA CoA) from the agent advertisement messages which are periodically advertised by mobility agents, or colocated CoA from an external mean like DHCP(CCoA). Then the mobile node sends a registration request message to its HA to register its new CoA. The HA updates mobile node information by associating the CoA of mobile node with the mobile node's IP address. Then the HA sends a registration replay message to the mobile host, either through the FA or directly, based on the CoA acquisition mechanism. Packets originated by the mobile node are received by the mobile node's HA. The HA locks up the CoA and tunnels packets to ether the mobile host's foreign agent (FA CoA) or to the mobile host (CCoA) based on the binding information, which is established using registration procedure.

Mobile Ipv4 suffers from some drawbacks like long handoff time and signaling overhead and this make it not suitable to support micro-mobility environment. Several improvements and enhancements for Mobile Ipv4 have been proposed, for



■ **Figure 2.** *Cellular IP access network.*



■ **Figure 3.** *HAWAII access network.*

example, MIPv4-RO [19], Mobile IPv6 [20].

Mobile IPv6 [20] is an enhancement for IPv6 [21], which enables IPv6 node to move from one IPv6 subnet to another without changing its IPv6 address. It is built based on the same principles of Mobile IPv4 and using the feature of IPv6. In Mobile IPv6, MN uses IPv6 Neighbor Discovery [22] to acquire a new CoA using IPv6 stateless address auto-configuration or state full address auto-configuration (such as DHCPv6 [23] or PPPv6 [24]). This CoA has the network prefix of the foreign subnet. Therefore, there is no need for a foreign agent. Mobile IPv6 defines two new IPv6 Destination Options, which are used for establishing a binding in the MN,s HA and corresponding node. These two IPv6 destination options are called the Binding Update option and Binding Acknowledgment option, respectively.

IP Micro-Mobility Protocols

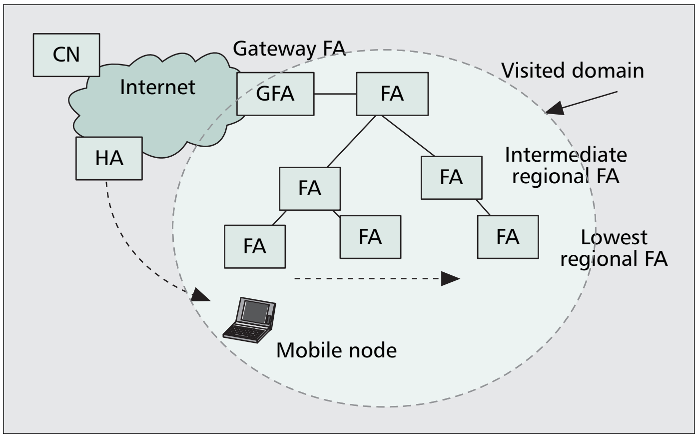
Micro-mobility is the movement (roaming) of mobile nodes between two subnets (or cells) within the same domain. In this environment, the mobile node changes its access point in the access network frequently; therefore, IP micro-mobility protocols are designed to handle the movement in this environment and provide fast and seamless handoff, such as Cellular IP [6–8], HAWAII [9, 10], HMIP [11], EMA [25], TelMIP [26], and so on. Cellular IP [6–8], from Columbia University and Ericsson, is proposed for handling mobility within the domain. It supports passive connectivity, fast handoff, and a paging mechanism. It can interwork with Mobile IP to provide a macro-mobility between domains. Cellular IP connects to the Internet through a gateway. Figure 2 illustrates the Cellular IP access network architecture and its components. It shows the mobile node movement in the domain.

Cellular IP replaces IP routing inside the domain, but without any change in IP packet format. Cellular IP maintains two types of distributed cache for location management and routing purposes. Packets transmitted by the mobile node create and update entries in each Cellular IP node's cache. The mobile node also maintains its routing cache mappings, even though it does not regularly transmit data packets, through transmit route-update packets on the uplink port at regular intervals called route-update time. When the mobile node moves to another access point, the chain of mapping entries always points to its current location because its route-update and uplink packets create new mapping and change old mapping. The mobile node connected to a Cellular IP network is always in either idle state or active state. The idle mobile node transmits a paging-update packet when the paging time expires. Paging update packets are used for location management; they are routed from base stations to the gateway using hop-by-hop shortest path routing.

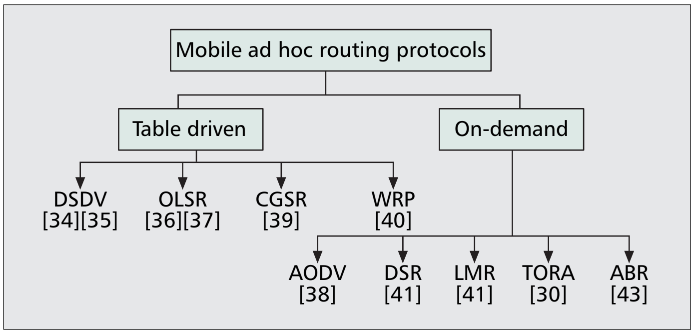
Handoff in Cellular IP is the movement from one access point to another access point during an ongoing data transfer. Cellular IP supports two types of handoff: hard handoff and semi-soft handoff. Hard handoff is optimized for wireless networks where the mobile node is able to listen/transmit to only one base station as in the case of a Time Division Multiple Access (TDMA) [29] network. Cellular IP base stations periodically emit beacon signals. Mobile nodes listen to these beacon signals and then initiate handoff based on signal strength measurements. The mobile node performs handoff procedure by tuning its radio to a new base station and then sending a route-update packet. The route-update packet creates or modifies routing cache entries in Cellular IP nodes to the gateway. The routing cache entries constitute a reverse path for the downlink packet to the new base station. When the crossover node receives the route-update packet, it diverts the incoming downlink packets towards the new base station. Data packets received by the old base station after the handoff will be dropped. Semi-soft handoff is optimized for networks where the mobile node is able to listen/transmit to two or more base stations simultaneously for a short duration, as in a Code Division Multiple Access (CDMA) [29] network. When a mobile node receives a beacon signal from a new base station, it sends a semi-soft packet to the new base station and immediately returns to listen to the old base station. The semi-soft packet creates new routing cache mappings from the new base station to the crossover node. The mobile node makes a final handoff decision after some delay called semi-soft delay. Cellular IP introduces delay at the crossover node to synchronize the delay difference between the old route and the new route from the crossover node in case the new route is shorter than the old route. The crossover node is notified that a semi-soft handoff is in progress from the semi-soft packet received from a mobile node that has mapping to another interface.

HAWAII [9, 10] is a domain-based IP micro-mobility protocol proposed to support the mobility within the domain. The domain connects to the Internet via a domain root router (DRR). Each mobile node has an IP address and a home domain. When the mobile node moves to a new foreign domain, it applies a Mobile IP handoff mechanism. Then it acquires a new collocated CoA. The CoA does not change during the movement of the mobile node between FAs in the same domain. Figure 3 illustrates HAWAII access network architecture and its components. It shows the intradomain and interdomain movement of the mobile node. The intradomain movement is handled within the domain using HAWAII, and the interdomain movement between different domains is handled using Mobile IP.

Hierarchical Foreign Agent (HFA) [11] is an extension to the basic Mobile IP to address the drawback of mobile IP through handling the IP micro-mobility of the mobile node within the domain. The basic network components are shown in Fig. 4. It consists of two or more hierarchy (tree like) levels of FAs. At the top of this hierarchy is one FA (or several) called a Gateway Foreign Agent (GFA). The GFA connects the domain to Internet by using a publicly routable address. At the bottom of the a hierarchy level are FAs, which enable the mobile node to access the domain and connect to internet. For multiple hierarchy levels, one (or more) FA called a Regional Foreign Agent (RFA) will be placed between the GFA and FAs, which are compatible with the GFA. In [25], a description of architecture for domain-based routing and addressing support, called EMA, is presented. This architecture does not specify how IP routing entries are created and modified. The TORA [30] ad hoc routing protocol can work with EMA to provide good scalability. In [26], a two-level hierarchy IP-based mobility architecture, called TeleMIP, is proposed. TeleMIP is scalable and it achieves small handoff latency and signaling overhead in comparison with Mobile IP. The major advantage of TeleMIP is that the FAs can be connected to more than one GFA within an administrative domain or a geographical region. In [31], an IP-based micro-mobility management protocol, called IDMP, is proposed. IDMP is an extension to the base micro-mobility protocol used in TeleMIP. Its major difference from other IP micro-mobility protocols is that it uses two dynamically auto-configured CoAs for routing packets towards the mobile node. Comprehensive surveys and comparisons of IP micro-mobility protocols can be found in [3, 14, 27, 28].



■ **Figure 4.** *HFA access network.*



■ **Figure 5.** *Mobile ad hoc routing protocols classification.*

Mobile Ad Hoc Routing Protocols

Routing in ad hoc wireless networks is a hot research topic, receiving wide interest from researchers [12, 13, 32, 33]. Many routing protocols have been proposed which tried to solve the routing problem. As shown in Fig. 5, these routing protocols have been classified according to their characteristics into two types: proactive (table-driven) routing protocols and reactive-source initiated (on-demand) routing protocols [32].

Proactive table-driven routing protocols maintain one or more routing tables in every node in order to store routing information about other nodes in the MANET. These routing protocols attempt to update the routing tables information either periodically or in response to change in network topology in order to maintain consistent and up-to-date routing information. Every routing protocol uses a different method for routing update broadcast and updating routing tables, and they use different number of routing tables. The advantage of these protocols is that a source node does not need a route-discovery procedure to find a route to a destination node, which causes some delay to initiate the connection. The route to destination is available from the routing table. The drawback of these protocols is that maintaining a consistent and up-to-date routing table requires substantial messaging overhead, which consumes bandwidth and power usage, and decreases throughput, especially in the case of a large number of high-mobility mobile nodes. In the next section we describe two of these routing protocols, DSDV [34, 35] and OLSR [36, 37], which have been used by some of the integration solutions.

Reactive-source initiated (on-demand) routing protocols initiate a route discovery mechanism by the source node to discover the route to the destination node when the source node has data packets to send to the destination node. After discovering the route, the route maintenance is initiated to maintain this route until the route becomes no longer required or the destination is not reachable. The advantage of these protocols is that overhead messaging is less. One of the drawbacks of these protocols is the delay of discovering a new route. In the next section we describe one of these routing protocols, AODV [38], which has been used by some of the integration solutions.

MANET routing protocols are mainly developed to maintain route inside MANET, and they do not utilize access points to make connection with other nodes in the Infrastructure network and Internet. In this article most of the proposals for integrating the MANET with the Internet are presented.

Proactive Table-Driven Routing Protocols

In this section a description of two proactive table-driven routing protocols, DSDV and OLSR, is given. It is observed above that only these two proactive table-driven routing protocols have been used in the integration solutions for routing. DSDV [34, 35] is a proactive (table-driven) ad hoc routing protocol based on the classical distributed Bellman–Ford algorithm to compute the route, but DSDV guarantees loop-free routing tables. Every mobile node in the network maintains a routing table that has an entry for every possible destination within the ad hoc network. Every entry in the routing table has the following field: destination address (or ID), next hop address (or ID), hop-count metric, installation time, and sequence number. The hop-count metric is the minimum number of hops between the source and the destination. The sequence number is assigned by the destination and used to mark the entry in order to recognize the stale route from the new route. Routing table updates are transmitted to every node in ad hoc network either periodically or triggered. Triggered updates are transmitted in response to change in network topology. Route update can be generated using full dump or incremental dump. Full dump means that the full routing table is broadcast through the ad hoc network. Incremental dump means that only information in the routing table entries, which has changed since last full dump, is broadcast through the ad hoc network in one route update packet. The route update packet includes the accessible destination nodes, the number of hops to each destination, and the sequence numbers assigned by source to each route. When a node receives a route update packet, it replaces the route, which has the old sequence number, with the new route. In case both the old and new routes have the same sequence number, the route with a lower hop-count number will be chosen in order to be used as a short path to the destination. The update information will be broadcast to neighbors. When a link to the next hop is broken, the node assigns an infinite value along with a new sequence number to every route that uses this link as next hop, and it will be triggered to broadcast the route-update packet. DSDV prevents fluctuations in the route update by delaying advertising any new routing update information to the network for period of staling time. This reduces the number of route-update messages. Accordingly, this will reduce network traffic and optimize routes.

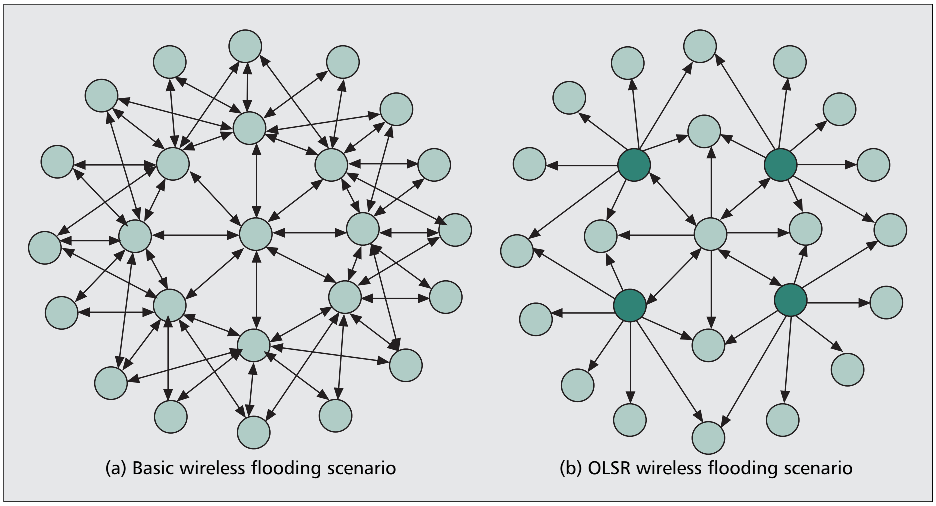


Figure 6. *a) Basic wireless flooding scenario and b) OLSR wireless flooding scenario.*

Optimized Link State Routing (OLSR) [36, 37] is a proactive, table-driven routing protocol developed as an optimization of the basic link-state algorithm for the mobile ad hoc network. It uses selected nodes called multipoint relays (MPRs) for the job of forwarding broadcast messages during the flooding process in order to reduce the control traffic overhead; this is the key idea behind OLSR. A basic wireless flooding scenario in the mobile wireless ad hoc network is depicted in Fig. 6a, where the arrows denote all transmission. Figure 6b shows flooding of a packet in the OLSR from the center node using MPRs. In Fig. 6b the black nodes are the MPRs, which forward packet to all neighbors.

OLSR supports three message types for handling and managing routing information in an ad hoc network:

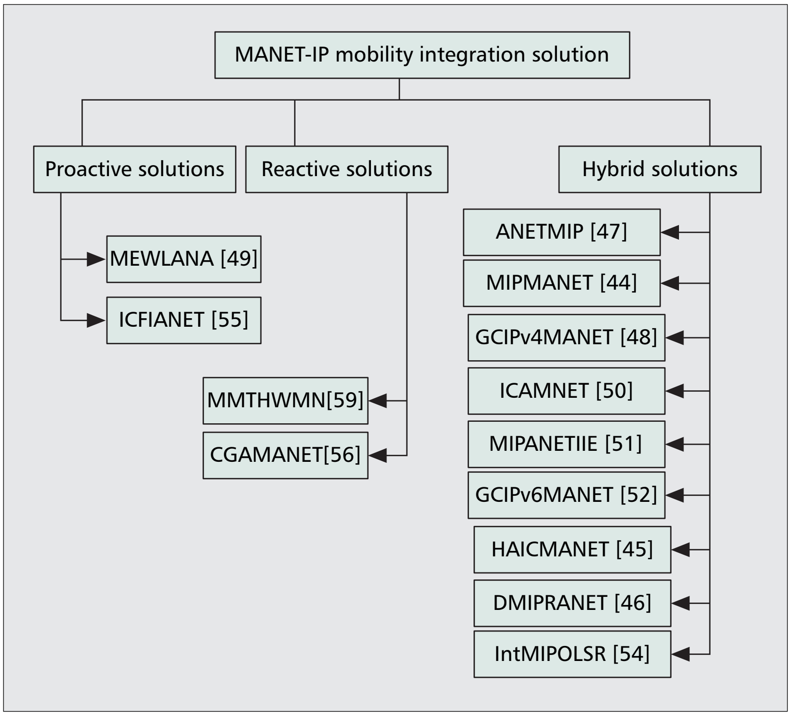
- HELLO-messages, which are sent periodically to node neighbors for populating the local link Information base and the neighborhood information base. OLSR uses the HELLO-messages exchange mechanism for link sensing, neighbor and topology detection, and MPR signaling.
- TC-messages: OLSR nodes use these messages to carry topology information to the other nodes in the network. Every node in an ad hoc network maintains topology information for use in routing table calculation.
- MID-messages: each node with multiple interfaces periodically sends MID-messages in order to declare its interface configuration to the other nodes in the network.

Each node X in the ad hoc network selects a set of nodes called MPR set for retransmitting broadcast messages. Other neighboring nodes, which are not in X's MPR set, receive and process broadcast messages, but do not retransmit broadcast messages which are received from node X. A node X selects it MPR set in a way that they are one-hop symmetric neighbors of node X and they cover all symmetrically strict two-hop nodes to X. This means that the broadcast message, which is sent by a node to its MPR node, will be received by all nodes two hops away. For neighbor discovery, a node periodically broadcasts a HELLO messages to its neighbor. When a node receives a HELLO message, it checks its address. If its address is found in the HELLO message, it registers the link to the source of the HELLO message as symmetric. If its address is not found, it registers the link to the source as asymmetric. Each node in the ad hoc network sends TC-messages periodically and when the MPR selector set is changed. TC-messages are flooded in the ad hoc network according to MPR flooding mechanisms. TC-messages contain information about network topology such as the MPR selector set, which is used to build a topology table and for route calculation. Each node has a routing table, which is computed from the link-state information base and the topology set. These information sets are updated from the periodic control messages and the interface configuration of the nodes. OLSR node runs the shortest-path algorithm to compute the route to every destination in the ad hoc network. The OLSR node runs the shortest-path algorithm each time a change is noticed in any of the following: the link set, the neighbor set, the two-hop neighbor set, the topology set, or the multiple interface association information base.

Numerous table-driven routing protocols have been proposed and implemented, and each one tries to solve the routing problem in particular situation; examples of such protocols are the Cluster Gateway Switch Routing (CGSR) protocol [39], the Wireless Routing protocol (WRP) [40], and so forth.

Reactive (On–Demand) Routing Protocols

In this section a description of one reactive- source initiated (on-demand) routing protocol, called Ad hoc On-demand Distance Vector (AODV), is given. It is observed that only AODV has been used as a proactive (table-driven) routing protocol in the integration solutions for routing given in the next section. AODV [38] is an on-demand reactive mobile ad hoc routing protocol, which is built based on the basics of DSDV routing protocols like using hop-by-hop routing, sequence number, and periodic beacon, but it does not require that nodes maintain routes to destinations that are not in active communication. AODV has some similarities with the DSR [41] routing protocol, such as using the route discovery process and route maintenance. Whenever a source has a



■ **Figure 7.** *Integration Solutions classification based on Gateway discovery.*

Category	Integration Routing Solutions
Tunneling based	MIPMANET [44] (2000) HAICMANET [45] March (2003) DMIPRANET [46] June (2004)
Non-Tunneling	ANETMIP [47] (1997) GCIPv4MANET [48] (2001) MMTHWMN [59] (2001) MEWLANA [49] Sept (2002) ICAMNET [50] April (2002) MIPANETIIE [51] May (2003) GCIPv6MANET [52] Feb (2003) IntMIPOLSR [53, 54] July (2004) ICFIANET [55] Oct (2004) CGAMANET [56] (2005)

■ Table 1. *MANET-IP mobility integration solutions.*

packet to transmit, it checks its routing table for a route to the destination. If it does not have a valid route to the destination, it invokes a route discovery process to find a route to destination. The source broadcasts a route request (RREQ) message to its neighbors. Each node checks the RREQ message, if it is the destination or has a fresh enough route to the destination; it sends an RREP message to the source. If it is not the destination or does not have a fresh route to the destination, it rebroadcasts the RREQ message to its neighbors and so on. Each intermediate node that forwards the RREQ message creates a reverse route-to-source node, and so the RREP message uses the reverse route to reach the source node. AODV uses a destination sequence number for each routing entry in every node to prevent the loop. A destination sequence number is generated by the destination for every route information to be sent to the source node. A destination sequence number is updated when a node receives new information about the sequence number from RREQ, RREP, or RERR messages. A valid route is the entry for the destination whose sequence number is greater than sequence number in the RREQ message. Routes in AODV are maintained by periodically transmitting a HELLO message (every one second) in every node in the ad hoc network. If a node that has recently forwarded packets does not receive three consecutive HELLO messages from a neighbor, it concludes that a link to this neighbor is down. The node propagates a link failure notification message (an RRER with infinite metric) to its upstream neighbor towards the source node. Then the source node initiates the route discovery process to find a new route to the destination.

Numerous on-demand routing protocols have been proposed and implemented, and each one tries to solve the routing problem in a particular situation; examples of such protocols are Dynamic Source Routing (DSR) [41], Lightweight Mobile Routing (LMR) [42], the Temporally-Ordered Routing Algorithm (TORA) [30] routing protocol, and the Associativity-Based Routing (ABR) protocol [43].

INTEGRATE MANETS TO INTERNET AND IP MOBILITY SUPPORT

INTEGRATED ROUTING PROTOCOL CLASSIFICATIONS

The characteristics of the ad hoc network and its routing protocols differ substantially from fixed Internet and IP mobility protocols. Numerous integration solutions for integrating MANET with the Internet using IP Mobility protocols have been developed as the trend of moving to an all-IP environment. As shown in Fig. 7, these integrated routing protocols may generally be categorized based on gateway discovery procedure as:

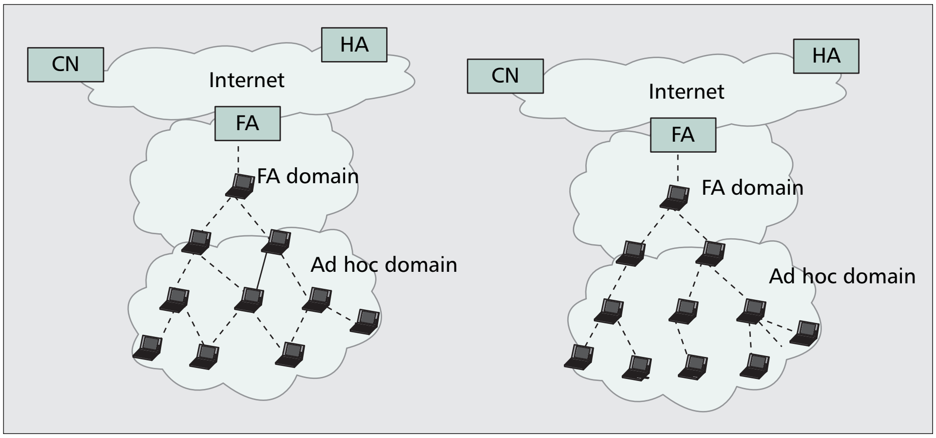
- Proactive solutions
- Reactive solutions
- Hybrid solutions

Integration solutions for routing can also be classified into two categories, as given in Table 1: tunneling-based-integration routing solutions and nontunneling-based-integration routing solutions

- Tunneling-based-integration routing solutions: In this approach, when the mobile node wants to send packet to destination, it first looks for the destination (using route discovery procedure as in AODV or searching in routing table as in DSDV or based on address network ID). If the destination address is located inside the MANET, it simply forwards packets using ad hoc routing protocol. If the destination address is not found in the MANET, it encapsulates packets and routes them to the FA (gateway). Then the FA decapsulates packets and sends them to destination using standard IP forwarding.
- Nontunneling-based-integration routing solutions: In this approach, if the destination address is not located inside the MANET, the mobile node sends packets to default route, which is the route to the FA (gateway). Every node should be able to distinguish external address from internal address and has a default route to the gateway node, or every node should establish route to gateway node during route discovery. Packets are transmitted inside MANET to destination in the Internet using standard IP forwarding. The gateway forwards data packets using standard IP forwarding.

INTEGRATION ISSUES AND SOLUTIONS

We now define some important issues for integrating MANETs with the Internet and supporting mobility between



■ **Figure 8.** *a) MEWLANA-TD and b) MEWLANA-RD.*

MANETs using IP mobility protocols. These will be the basis of our comparison.

- **Micro-mobility support**: Micro-mobility is the handle of high frequently movement of mobile node inside domain. Because of the characteristics of ad hoc routing protocols, which provide mechanisms to manage movement of nodes, micro-mobility support in the integrated routing protocol is an important metric.
- **Gateway discovery**: The gateway router is a node located between a fixed Internet access network and a mobile wireless ad hoc network, which is used to connect the MANET nodes to the Internet. It provides Internet connectivity for MANET nodes. The MANET node should discover the gateway information and its route in order to access Internet. When the MANET node moves inside a MANET with multiple gateways, it should be able to discover and select the gateway with the optimal route. Therefore, gateway discovery with minimum delay, minimum overhead, and optimal route is an important issue.
- **Tunneling**: In tunneling, the mobile node encapsulates packets and sends them to the gateway node. The intermediate nodes look up the destination node route and they forward packets to the destination. When the gateway node receives packets, it decapsulates them and sends them to the original destination.
- **Periodic Agent Advertisement**: A gateway node (or FA) periodically broadcasts agent advertisement messages on their wireless channel to all mobile nodes in its coverage area. The agent advertisement message contains information such as CoA, which enables mobile nodes to register with the gateway node and get Internet connectivity. The agent advertisement message should be flooded to all MANET nodes, which are out of gateway node coverage area. Use of the agent advertisement message is an important metric that can be considered to study the integration routing protocols performance.
- **Movement detection/handoff decision**: Handoff in the integration routing solution is used for route optimization. When a mobile node detects a new gateway with a short path, it initiates the handoff to the new gateway and this will optimize the route. Most of the integrated approaches use hop count as a metric for handoff decision. The handoff decision depends on the movement detection method. There are two methods for movement detection: receiving the agent advertisement message and invalidating the route entry

In the following, we provide an overview of 13 different integration routing solutions by describing their characteristics and functionality and categorizing them according to their characteristics.

Proactive Integration Routing Solutions — In the proactive solutions, agent advertisement messages are broadcast by gateway nodes and forwarded to the whole ad hoc network. The agent advertisement message is used for gateway discovery, creating default route, mvement detection, and handoff decision based on number of hops. The proactive integration routing solutions details are given below.

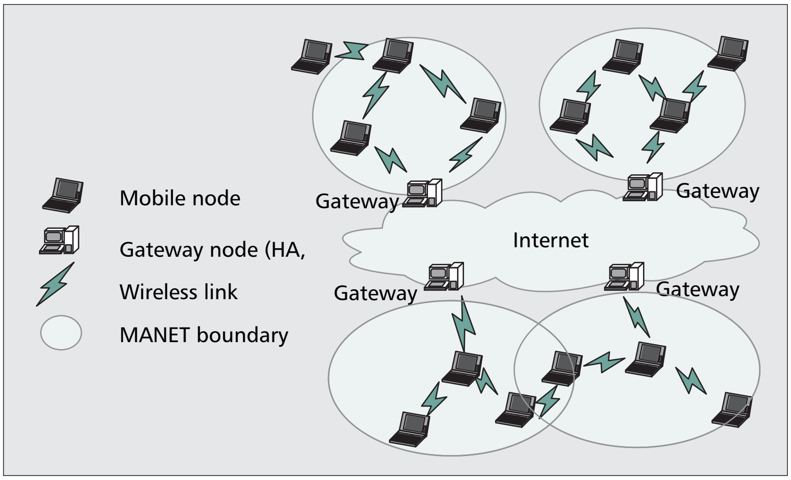
MEWLANA: Mobile IP Enriched Wireless Local Area Network Architecture — In "MEWLANA" by Mustafa Ergen [49], two protocols to extend Mobile IP capabilities to ad hoc networks are proposed. They are called MEWLANA-TD and MEWLANA-RD. Three types of domains are considered, namely, the Internet domain, the FA domain, and the ad hoc domain, as shown in Fig. 8.

MEWLANA-TD uses the DSDV routing protocol to route packets between the FA and mobile ad hoc nodes; Fig. 8a shows the routing path between mobile nodes to the FA using DSDV. In MEWLANA-RD, a proposed root-driven ad hoc protocol called table-based bidirectional Routing (TBBR) is used to route packets between ad hoc mobile nodes and the FA. In this protocol, the routing table in every node has two types of entries. The first type is established when the mobile node receives a periodic beacon from the FA, which refers to the default route to the FA (uplink port). The second type is established when the mobile node receives registration request message from low-level mobile node. This entry is used as down link port; Fig. 8b shows the routing path between mobile nodes to the FA using TBBR.

Integrated Connectivity Framework for Internet and Ad hoc Networks — In [55], an enhancement for the DSDV protocol has been proposed to solve the link break problem due to high mobility, which decreases the performance of the standard DSDV protocol. It proposes a bidirectional connectivity for ad hoc networks and the Internet based on EDSDV. Three simple communication scenarios are presented a.

Reactive Integration Routing Solutions — In the reactive solutions, mobile nodes initiate route discovery so as to look for the gateway node. Mobile nodes send a route request message, or an agent solicitation message, to find the gateway node and route to it. This kind of solution cannot detect the mobile node movement to another gateway or take fast handoff decision. It uses invalidate route entry for movement detection and initiates gateway discovery. The reactive integration routing solutions details are given below.

Micro-mobility within Wireless Ad hoc Networks: Towards Hybrid Wireless Multihop Networks — In [59], the author proposes integration between Cellular IPv6 and AODVv6, which enables the mobile node to access the Cellular IPv6 network even if it is farther than one hop distance from base station. This integration approach has two different operation modes: proxy-enabled and proxy-disabled. The base station runs AODV and works as an access point for the mobile nodes. A mobile node initiates a route acquisition procedure for route discovery and Cellular IP registration. The mobile nodes sends a route request with an IPv6 multicast



■ **Figure 9.** *Integrated network architecture.*

address ALL-BS for base station discovery. The base stations send route replay with Cellular IPv6 beacon as the IPv6 destination options header. In proxy-enabled mode, the base station responds to the route request on behalf of the Cellular IPv6 gateway, and it also sends packets addressed to the Cellular IPv6 gateway. In this mode, an ad hoc route is established for the Cellular IPv6 gateway. The route-update packet and data packet are sent to the Cellular IPv6 gateway using IPv6 routing header. In proxy-disabled mode, the base station sends only one route request on behalf of itself. In this mode, the ad hoc route is only established to the base station and no ad hoc route is established for the Cellular IPv6 gateway. The route update packets and data packets are sent to the base station using IPv6 routing header. In proxy-enabled mode, the mobile node that is in the Cellular IPv6 base station coverage controls the handoff procedure. This mobile node sends route update and proxy-RU to the Cellular IPv6 gateway on behalf of each node having an active connection through it. In proxy-disabled mode, the handoff procedure depends on the mobile node that is in the Cellular IPv6 base station coverage. This mobile node sends a gratuitous RREP packet with a Cellular IPv6 beacon to every mobile node having an active connection through it on behalf of base station. Then the mobile node controls the handoff procedure by sending a route update packet to the Cellular IPv6 gateway via the new base station.

Common Gateway Architecture for Mobile Ad hoc Networks — In [56], an architecture for supporting multiple gateways for Internet access in the mobile ad hoc network is proposed. This architecture includes several access points, which are connected to one common Internet gateway, and represents part of the ad hoc network. The common gateway is not part of the ad hoc network. In this architecture, the AODV is selected as a MANET routing protocol. Three types of nodes are presented in the architecture as follows:

- Mobile nodes: ad hoc nodes running AODV routing protocol with some extension to enable it to discover the internet gateway
- Access points: routers running the AODV routing protocol which have two interface; one wireless which is connected to the ad hoc network and one wire which is connected to the gateway
- Gateway: a router that has a connection to all access points and another connection to Internet

This architecture manages the IP address space and run AODV with some extension required to connect to the Internet. When the gateway wants to find the route to any node in the ad hoc network, it sends an RREQ message to every access point. These access points send the RREQ message to its neighbors, and so on, to the destination. Then the destination sends an RREP message to the gateway, so that the route will be established from the gateway to the destination. The gateway selects the route with minimum hop count. If the gateway receives an RREQ message, it will send an RREP message through the access point, which sends the RREQ message to the gateway. If the route is lost, a new optimal route is established using the routing protocol (AODV).

Hybrid Integration Routing Solutions — In the hybrid solutions, both the proactive and reactive gateway discovery approaches, or a combination of the proactive and reactive approaches, are used. This kind of integration uses flood-periodic agent advertisement messages to announce the presence of the gateway nodes, and uses agent solicitation messages or the agent discovery procedure by mobile nodes to discover the gateway nodes. The hybrid integration routing solutions details are given below.

Ad Hoc Networking with Mobile IP — In this proposal [47], an ad hoc networking mechanism is designed and implemented, which enables mobile computers to communicate with each other and access the Internet. An adaptation for Mobile IP protocol is proposed. The proposed adaptation makes the FA to serve a mobile node, which is out of communication range. A modified Routing Information Protocol (RIP) [57, 58] is used to handle the routing inside the ad hoc network.

MIPMANET: Mobile IP for Mobile Ad Hoc Networks – In "MIPMANET — Mobile IP for Mobile Ad Hoc Networks" [44], a solution for integrating ad hoc networks to the Internet based on Mobile IP is proposed. This solution is proposed to provide mobile nodes in ad hoc networks with access to the Internet and the mobility service of Mobile IP. The FA is used as an access point to the Internet. The AODV routing protocol is used to route packets between the FA and the ad hoc nodes. When a new node wants to access the Internet, it registers with the FA using its home address. The mobile nodes in the ad hoc network tunnel the packets to the FA in order to send them to the Internet. The FA simply sends any packet coming from the Internet to the mobile node in the ad hoc network. Routing the packet inside the ad hoc network is based on the ad hoc routing protocol used, which in this case is AODV. MIPMANET uses the route discovery mechanism of the AODV routing protocol to search for the destination. If the route to destination is not found within the ad hoc network, the mobile node establishes a tunnel to the FA according to the FA default route the mobile node registers with.

Global Connectivity for IPv4 Mobile Ad hoc Networks — In this Internet draft [48], the authors proposed a method to enable MANET to obtain Internet connectivity. The method proposed in this Draft is integration between Mobile IPv4 and AODV, such that a mobile node outside the FA transmission range can get a CoA and connect withthe Internet through other hops in the MANET. It can roam to another MANET subnet without disconnection using Mobile IP.

Internet Connectivity for Ad hoc Mobile Networks — This research work [50] is similar tothe Internet Draft described in [48]. It presents integration between Mobile IP and AODV. The authors combine the mobile IP and AODV such that the mobile node in the ad hoc network can obtain Internet connectivity and roam to another subnet.

Mobile IP and Ad Hoc Networks: An Integration and Implementation Experience — In [51], integration of a MANET with the Internet is proposed. In this integration, one-hop wireless networks are extended to multiple MANETs. Every MANET is served by an FA (access point), and it represents a subnet of the Internet. The proposed architecture consists of multiple MANETs connected to the Internet using different access points called gateways. Figure 9 shows this architecture.

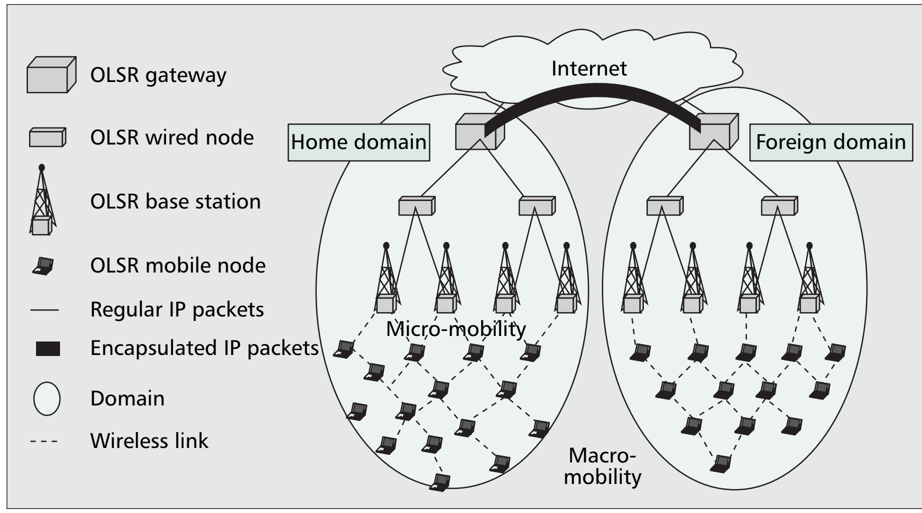


Figure 10. *OLSR-IP network architecture.*

Global Connectivity for IPv6 Mobile Ad Hoc Networks — This Internet Draft [53] describes a method to enable MANET nodes to communicate with the fixed Internet. The connection between the MANET nodes and the Internet is through nodes called Internet-gateways, which are connected to the Internet using a wired interface and connected to MANET using a wireless interface. The author has proposed two methods to enable MANET nodes to find the Internet-gateway and obtain the global prefix information, so that the MANET node can generate a global IPv6 address, which is used for sending/receiving packets from/to the Internet.

A Hybrid Approach to Internet Connectivity for Mobile Ad Hoc Networks — In [45], the authors proposed a hybrid scheme to enable the MANET nodes to obtain Internet connectivity using Mobile IP. The FA periodically broadcasts agent advertisement messages. The agent advertisement messages are flooded in the MANET in an *n*-hop neighbor. Any node, *n* hops far from the FA, can receive up-to-date information about the FA. Mobile nodes more than *n* hops away from the FA and wanting Internet connectivity broadcast a solicitation message to discover the FA. The intermediate node, which receives a fresh agent advertisement message and has a correct route to the FA, can reply to the mobile node with a unicast advertisement.

Dynamic Mobile IP Routers in Ad Hoc Networks — In [46], integration between cellular system (GPRS) and ad hoc networks is presented using Mobile IP. The basic idea in the integration is using mobile routers as a gateway between the HA and ad hoc mobile nodes. It is assumed that gateways (mobile routers) in the ad hoc network are multi-interfaced. One interface is connected to the cellular system and the other connected to the ad hoc network using the ad hoc routing protocol. The mobile router sets up tunnels to every mobile node for which it is serving as gateway, and another tunnel to the HA using second interface.

Integration of Mobile-IP and OLSR for Universal Mobility — In [54], by Moner Binzaid *et al.*, a hierarchical mobility management architecture is proposed and used to interconnect MANET nodes to the Internet. The access network of the proposed integrated network architecture is called OLSR-IP access network. It includes several functional entities, as shown in Fig. 10.

Comparison and Summary

In this section a comparison summary of the integration routing solutions, based on the abovementioned integration issues, is presented. A summary of the Proactive Integration Routing Solutions characteristics and design issues is given in Table 2.

A summary of the Reactive Integration Routing Solutions characteristics and design issues is given in Table 3. A summary of the Reactive Integration Routing Solutions characteristics and design issues is given in Tables 4 and 5. Table 6 gives a general comparison between the groups of integration solutions. In the following, we present issue-by-issue comparison of the integration routing solutions.

Micro-Mobility Support

From Tables 2–5, it can be concluded that most of the integration solutions are used to connect MANET to the Internet and support mobility using Mobile IP, but a few of these integration solutions try to integrate MANET to the Internet and support micro-mobility between multiple access points (gateway nodes, as in [51, 54, 56, 59]), and only the integration solution presented in [59] tries to utilize IP micro-mobility protocols for supporting MANET mobile-node Internet connectivity and mobility between different base stations. None of these integration protocols employ IP micro-mobility protocols [3, 14] for supporting mobility between different overlap and none overlap MANETs with multiple access points within domain, whereas such a proposal is recommended for integrating MANET to infrastructure networks and support mobility between multiple nonoverlap and overlap MANETs with multiple access points.

Gateway Discovery

The proposals that use reactive gateway discovery required a long time to access and send packets to the Internet. If the node wants to access and send packet to the Internet, it needs first to send route discovery. If the destination is not in the MANET, it sends a route discovery for the gateway. So it takes a long time for the discovery process. Some proposals need only one route discovery process. In the integrated solutions, which uses proactive gateway discovery, a route to the gateway node is available when it is needed; such proposals are presented in [44, 47, 49, 51, 54, 55]. If the destination address is not in the routing table, the default route to gateway node should be used. The integration routing solutions have been classified on the basis of gateway discovery into

Proactive Approaches	MEWLANA [49] Sept. (2002)	ICFIANET [55] Oct. (2004)
1. Micro-Mobility support	No	No
2. Gateway Discovery	1 method	1 method
3. Tunneling	No	No
4. Periodic Agent Adv	Yes	No
5. Movement Detection	Hop count	Infinite hop count metric
6. Handoff decision	Hop Count	Infinite hop count metric
7. Mobile IP	MIPv 4	MIPv 4
8. Ad hoc Routing	DSDV&TBBR	EDSDV
9. Implementation Approach	Adjusting Mobile IP to work with DSDV and support TBBR	Adjusting DSDV to support Mobile IP
10. Periodic Unicast Agent Adv.	No, it is mentioned as a proposal	No
11. Use Agent Solicitation for Gateway discovery	No, it is mentioned as a proposal	No
12. Incorporate Default Route concept to Ad hoc routing protocol	Yes	No
13. Routing between MANET nodes and Gateway	Using route established by agent advertisement message	According to EDSDV protocol.

■ Table 2. *A summary of the proactive integration approaches..*

Reactive Approaches	MMTHWMN [59] (2001)	CGAMANET [56] (2005)
1. Micro-Mobility support	Yes	Yes
2. Gateway Discovery	1 method	1 method
3. Tunneling	No	No
4. Periodic Agent Adv.	No	No
5. Movement Detection	Controlled by MN in the base station coverage	Invalidated the route entry.
6. Handoff decision	Controlled by the MN in the base station coverage	Invalidated the route entry
7. Mobile IP	Cellular IPv 6	No
8. Ad hoc Routing	AODVv 6	AODV
9. Implementation Approach	Combining of Cellular IPv 6 and AODVv 6	Adjusting AODV to handle micro-mobility
10. Periodic Unicast Agent Adv.	No	No
11. Use Agent Solicitation for Gateway discovery	Use route acquisition	No
12. Incorporate Default Route concept to Ad hoc routing protocol	No	Yes
13. Routing between MANET nodes and Gateway	It utilizes IPv 6 routing header	According to AODV protocol

■ Table 3. *A summary of the reactive integration approaches.*

Hybrid Approaches	ANETMIP [47] (1997)	MIPMANET [44] (2000)	GCIPv4MANET [48] (2001)	ICAMNET [50] April (2002)	MIPANETIIE [51] May (2003)
1. Micro-Mobility Support	No	No	No	No	Yes
2. Gateway Discovery	2 methods	2 methods	2 methods	2 methods	2 methods
3. Tunneling	No	Yes	No	No	No
4. Periodic Agent Adv.	Yes	Yes	Yes	Yes	Yes
5. Movement Detection	Receiving Agent advr. from new FA.	MIPMANET Cell switching Algorithm	As in MIPv4	Receive agent adv. from new FA	As in MIP
6. Handoff decision	Shortest distance	MIPMANET Cell switching Algorithm	As in MIPv4	If MN has not received agent Adv. From registered FA.	Shortest distance
7. Mobile IP	MIPv4	MIPv4	MIPv4	MIPv4	MIPv4
8. Ad hoc Routing	*Modified RIP*	AODV	AODV	AODV	DSDV
9. Implementation Approach	Adjusting Mobile IP work with Modified RIP	Adjusting Mobile IP to work with AODV	Adjusting Mobile IP to work with AODV	Adjusting Mobile IP to work with AODV	Adjusting Mobile IP to work with DSDV
10. Periodic Unicast Agent Adv.	No	No	No	No	No
11. Use Agent Solicitation for Gateway discovery	Yes	Yes	No	No	Yes
12. Incorporate Default Route concept to Ad hoc routing protocol	Yes	Yes	FA as default route	No	Yes
13. Routing between MANET nodes and Gateway	According to a modification to a modified RIP	Using tunneling	Normal IP forwarding	Standard IP forwarding	Based on DSDV routing

Table 4. *Summary of the hybrid integration approaches.*

three categories:
- Proactive: In the proactive solution [49, 55], the agent advertisement messages are broadcast by gateway nodes and forwarded to the whole ad hoc network. The agent advertisement message is used for gateway discovery, creating a default route, and movement detection and handoff decision based on number of hops. This kind of integrated solution provides good Internet connectivity if most of the mobile nodes need Internet connectivity. But it generates an overhead in an ad hoc network if most of the mobile nodes are not interested in Internet connectivity and most of the traffic is inside the ad hoc network.
- Reactive: In the reactive solution [59, 56], mobile nodes initiate route discovery to look for gateway nodes. Mobile nodes send a route request message, or an agent solicitation message, to find the gateway node and the route to it. This kind of solution cannot detect the mobile node movement to another gateway or make a fast handoff decision. It utilizes invalidate route entry for movement detection and initiates gateway discovery. The reactive approach requires a long time to access and send packets to the Internet. If the node wants to access and send packets to the Internet, first it needs to send a route discovery. If the destination is not in the MANET, it sends a route discovery for the gateway. Thus, the discovery process takes a long time. Some proposals use only one route discovery process. In the integrated solution, which uses proactive routing protocols, route to destination is available when it is needed.
- Hybrid: The Hybrid Solution [44–48, 50–52, 54] uses proactive and reactive gateway discovery approaches, or a combination of the proactive and reactive approaches. Using a combination of the proactive and reactive approaches has some advantages, for example, it decreases the agent advertisement-flooding overhead. It uses a flood-periodic agent advertisement message, but to a limited number of nodes, called a MANET diameter. It uses an agent solicitation message or the agent discovery procedure for mobile nodes, which are out of the agent advertisement message's reach, as in [45].

Tunneling

In integration routing solutions, which use tunneling, the mobile node encapsulates packets and sends them to the gateway node. Intermediate nodes look up the destination node route and forward the packets. When the gateway node receives the packets, it decapsulates packets and sends them

Hybrid Approaches	GCIPv6MANET [52] Feb (2003)	HAICMANET [45] March (2003)	IntMIPOLSR [53, 54] July(2004)	DMIPRANET [46] June (2004)
1. Micro-Mobility Support	No	No	Yes	No
2. Gateway Discovery	2 methods	2 methods	2 methods	2 methods
3. Tunneling	No	To FA=yes, from FA=no;	No	Yes
4. Periodic Agent Adv.	No	Yes	Yes	Yes
5. Movement Detection	As in MIPv6	Using MMCS Cell switching Algorithm [44]	OLSR for micromobility, and MIP for macromobility	Receive Agent Adv. From different Mobile Router.
6. Handoff decision	As in MIPv6	Using MMCS Cell switching Algorithm [44]	OLSR for micromobility, and MIP for macromobility	Based on TTL value
7. Mobile IP	MIPv6	MIPv4	MIPv4	MIPv4
8. Ad hoc Routing	AODVv6	AODV	OLSR	AODV
9. Implementation Approach	Adjusting Mobile IPv6 to work with AODVv6	Adjusting Mobile IP to work with AODV	Adjusting OLSR to support micromobility	Adjusting Mobile IP to work with AODV
10. Periodic Unicast Agent Adv.	No	No	No	No
11. Use Agent Solicitation for Gateway discovery	Yes	Yes	Yes	Yes
12. Incorporate Default Route concept to Ad hoc routing protocol	Yes	No	No	No
13. Routing packets between MANET nodes and Gateway	Using default route	Using Tunneling and AODV	Based on OLSR routing	Using Tunneling

■ Table 5. *A summary of the hybrid integration approaches(cont.)*

to original destination. The use of tunneling inside the MANET makes forwarding packets transparent to the MANET routing protocol. But tunneling has some drawbacks such as increased packet size and increased packet processing time. The use of tunneling can prevent the loop inside the MANET in the routing of data packets to a destination in the Internet, and can make routing packets independent of topology changes within the ad hoc network. It is the MANET routing protocol's responsibility to find a path to the end of tunnel.

In the integration solutions, which use tunneling, each node in the MANETs should incorporate the default route to the gateway node in the MANET routing protocol's routing table. The integrated routing solutions have been classified into two categories:
- Tunneling-based integration routing solutions [44–46]
- Nontunneling-based integration routing solutions [47–52, 54–56, 59]

Periodic Agent Advertisement

It is observed that using agent advertisement messages in integration solutions has many advantages:
- They can be used for gateways discovery
- They can be used for acquiring gateways information such as CoA
- They can be used to create default route in each mobile node
- They can be used to set up MANET diameter in case of overplayed MANETs
- They can be used for movement detection and handoff decision
- They can be used to establish route to gateway node, such that the mobile node can use this route to transmit data packets to the Internet

Also, it is observed that periodically broadcast agent advertisement message can increase the traffic and generate an overhead in ad hoc network. As shown in Tables 2–5, the roposals in [45–51, 54] use periodic agent advertisement. On the other hand, the proposals in [52, 55, 56, 59] do not use it; they are reactive for gateway discovery.

Movement Detection/Handoff Decision

Most of the integrated proposals use hop count as a metric for handoff decision. The handoff decision depends on the movement detection approach. There are two methods for movement detection:
- The method based on agent advertisement message, as in [44–52]
- The method based on invalidate route entry of the ad hoc routing protocol routing table, as in [54–56, 59].

	Proactive Approach [49, 55]	Reactive Approach [56, 59]	Hybrid Approach [44–48, 50–52, 54]
Periodic Agent Advertisement	Yes	No	Yes
Using Agent Solicitation for Gateway discovery	No	Yes	Yes
Gateway Discovery	1 method (Proactive)	1 method (Reactive)	2 methods (Proactive

■ Table 6. *Comparison of the 3 integration approaches.*

Finally, we present a comparison summary for three other important design issues in the integrated proposals.

Gateway (FA) Discovery Procedure

ANETMIP [47] uses two methods for gateway discovery. ANETMIP [47] discovers the gateway either by listening for agent advertisement broadcast by the FA, or by sending an agent solicitations message. We can observe that the ANETMIP [47] gateway discovery methods are a modification to the mobile IP agent discovery methods, such that the agent advertisement message or the agent solicitation message can travel more than one hop to reach the mobile node or the FA. In ICAMNET [50] and GCIPv4MANET [48], two methods are used for discovering the gateway. In the first, the mobile node can learn the FA and its IP address from the periodic agent advertisement messages. In the second, the mobile node issues a route request of the AODV for the "All Mobility Agents" multicast group address. We can observe that the first method is a modification of mobile IP and the second method is a modification of the AODV routing protocol. MMTHWMN [59] uses a reactive approach for gateway discovery. The mobile node sends AODV route request with an IPv6 multicast address ALL-BS and, based on the protocol operation mode, the base station's response to the route request along with beacon packet. MIPANETIIE [51] uses the same gateway discovery procedures used in ANETMIP [47], but in MIPANETIIE [51], the mobile node sets the destination field to the all-routers multicast address 224.0.0.2 in the multicasts agent solicitation in order to find a nearby mobile agent. MIPMANET [44] uses the same methods used in ANETMIP [47] for gateway discovery, which are a modification to mobile IP agent discovery methods. In HAICMANET [45], three methods are used for discovering the gateway, either by monitoring any agent advertisement message and recording the address of the FA, or by broadcasting agent solicitation to discover an FA, or a combination of the first and second. In IntMIP OLSR [53, 54] two methods are used for discovering the gateway, either by receiving a periodic agent advertisement message from OLSR-GW, or by sending agent solicitation message. The IntMIP OLSR [53, 54] uses the OLSR routing protocol to handle the broadcasting of agent advertisement and agent solicitation messages inside the access networks, so that the gateway discovery broadcast overhead is less than that of other proposals. DMIPRANET [46] uses two methods for gateway discovery, either through sending a solicitation message requesting agent (gateway) services, and then receiving the agent advertisement message, or by waiting for the periodic agent advertisement message. In MEWLANA [49], mobile nodes use only agent advertisement to discover the access point (gateway) to the Internet. In ICFIANET [55], the gateway discovery is totally based on the modification to the MANET routing protocol , a host broadcasts DSDV advertisement to its neighbors, in order to establish routing table, so that a mobile node and an FA automatically know each other's presence via routing update of EDSDV protocol. In GCIPv6MANET [52], two methods for gateway discovery are used. The first uses an extended route discovery messaging of on-demand routing, and the second uses an extended router solicitation and advertisement of the Neighbor Discovery Protocol (NDP). In CGAMANET [56], the gateway address is preconfigured in mobile nodes. Another method uses AODV with any of the gateway discovery procedures.

Destination Route Discovery and Packets Transmission

In MIPMANET [44], the mobile node lets the route discovery mechanism of the ad hoc routing protocol search for the destination before it can decide whether or not the destination is within the ad hoc network. Then it simply tunnels packets to the FA. In GCIPv4MANET [48], the mobile node discovers the route to external destination either by using route created using FA_RREP from the gateway node, or if the route to destination is not discovered within the MANET, the mobile node uses path created using agent advertisement message. In MMTHWMN [59], the mobile node uses AODVv6 route discovery to search for the destination; if it is not found, it initiates route discovery and sends RREQ with an IPv6 multicast address ALL-BS. When the base station receives the RREQ packet, it replies with the RREP packet, which establishes the route from the mobile node to the base station or to the Cellular IPv6 gateway. The mobile node utilizes the IPv6 routing header for sending data packets. In ICFIANET [55], the mobile node checks its routing table. If the route entry is found, packets will be forwarded inside the ad hoc network. If the route entry is not found, the mobile node checks the route to the FA. If the route to the FA is found, packets will be forwarded to the FA gateway towards the Internet; otherwise, the packets will be discarded. In HAICMANET [45], the same procedure as in MIPMANET [44] and ICFIANET [55] is used. If no route reply is received except FA_RREP, the mobile node discovers that the destination is located outside the MANET. Then, the packets are encapsulated and routed to the FA. Also, the agent advertisement message is used to set up the reverse route to the mobile node. In MIPANETIIE [51], if the destination address is not listed in the kernel routing table, the packets will be forwarded to the gateway. In DMIPRANET [46], if the destination address cannot be reached using ad hoc routing, the packets will be forwarded using tunneling to the mobile router. It can be observed that MIPMANET [44], HAICMANET [45], and DMIPRANET [46] use the idea of tunneling for data packets transmission inside MANET toward the external destination. In MEWLANA [49], the mobile node checks its routing table: if the route entry is found, the packets will be forwarded inside the ad hoc network; if the route entry is not found, the mobile node routes packets to the FA gateway (default route) towards the Internet. Also, IntMIP OLSR [53, 54] uses the same procedure used in MEWLANA [49]; routes to each node are immediately available for all destinations in the access network, and these routes are computed with Dijkstra's shortest-path algorithm. In ANETMIP [47], the mobile node searches its kernel routing table. The kernel IP code looks up the matching route entry. If the selected route entry carries an

RTF_INDIRECT flag, the IP will have to do another look up for the indirect gateway returned in first look up. The second look up returns the link-layer address of next hop, which is used for packets transmission. In GCIPv6MANET [52], if mobile node does not have a route to the destination host, it sends a route request for the destination. If a reply is not received and a default route exists, the node uses the default route for packet transmission to the destination. In ICAMNET [50], there are two ways for destination route discovery and packets transmission, either using the route created from FA_RREP, or if the route to destination is not discovered within the MANET, the mobile node transmits packets to the FA using the path created by using the agent advertisement message. In CGAMANET [56], the mobile node has the ability to distinguish external address from the internal address. Then, it broadcasts the route request to establish the route to gateway using standard AODV operation.

Addressing

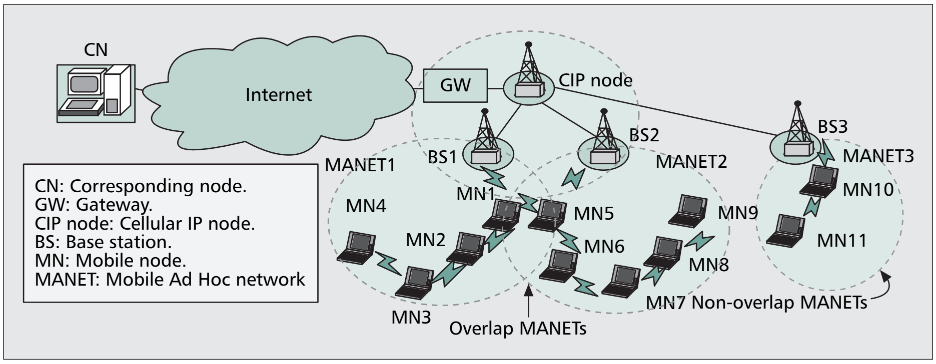
In GCIPv4MANET [48], the mobile node uses its home IP address in its home network as in Mobile IP, and it gets a globally routable IP address CoA on the visited network. The CoA in GCIPv4MANET [48] can be obtained in one of the following three ways:
- From an agent advertisement message
- By issuing an agent solicitation message
- By acquiring a collocated CoA

But in HAICMANET [45], every node has an arbitrary address, which is used within the MANET, and it uses the CoA acquired from the FA for external communication. In MIPMANET [44], the mobile node that wants Internet access has a home IP address that is valid on the Internet, and this home address can be used on the ad hoc network as well. In MMTHWMN [59], a mobile node uses a collocated CoA that it is formed from network prefix in the Cellular IPv6 beacon. In MIPANETIIE [51], every node should have two address: a home IP address and a CoA as in Mobile IP. IntMIP OLSR [53, 54] uses the same addressing as in MIPANETIIE [51]: every mobile node has two IP addresses, a home IP address and a CoA. The CoA is the IP address of OLSR-GW. In DMIPRANET [46], a mobile router connects to the Internet using a global IP address, and the mobile node uses a collocated CoA that it acquires for use on their WAN interface and uses its home address in the ad hoc network. For ICFIANET [55] and MEWLANA [49], every node should have a routable IP address, a home IP address that is used for routing inside MANET, and an FA address that is used as a CoA for every visited mobile node. In ANETMIP [47], every node has a home IP address, which is used for communication with a host in the Internet or a host inside MANET, as in Mobile IP. In GCIPv6MANET [52], the mobile node gets the global prefix information of the Internet-gateway and uses it for configuring a routable IPv6 address.

A Framework for Integrating Cellular IP Access Network and Mobile Ad Hoc Networks

Based on the above survey and comparison, we observed that most of the abovementioned solutions aim to support MANET with Internet connectivity based on Mobile IP and do not support micro-mobility; a few of these integration solutions try to integrate MANETs to the Internet and support micro-mobility between multiple access points (gateway nodes) as in [51, 54, 56, 59]). Only the integration solution presented in MMTHWMN [59] tries to utilize IP micro-mobility protocols for supporting MANET mobile node Internet connectivity and mobility between different base stations, but it has many drawbacks and limitations. MMTHWMN [59] is proposed for the Cellular IPv6 network and AODVv6 routing protocol, and it cannot work with Cellular IPv4 networks. The handoff procedure in MMTHWMN [59] is not efficient and reliable because the handoff procedure of the mobile node in MMTHWMN [59] is controlled by another mobile node located in the base-station coverage area. The packet transmission, route discovery, and handoff in MMTHWMN [59] are not transparent to the MANET mobile nodes. The mobile node located in the base station coverage area sends a proxy-RU on behalf of each mobile host having an active connection with it to the base station, and it send a gratuitous RREP packet with a Cellular IPv6 beacon on behalf of base station-to-mobile nodes, and this dependency on another mobile nodes make it not efficient nor reliable for fast mobility and handoff. And none of the above surveyed integration protocols employ IP micro-mobility protocols for supporting mobility between different overlapping and nonoverlapping MANETs with multiple access points within domain and support fast handoff, whereas such a proposal is recommended for integrating MANET to infrastructure networks and support fast handoff. Mobile IP, described above, is the most widely known IP mobility management proposal that supports host mobility. It is designed to enable the mobile node to change its point of attachment (access point) without changing the IP address. When the mobile node leaves the current network and enters a new foreign network domain, it acquires a new IP address called IP CoA and informs its HA about the new IP CoA. Mobile IP is an optimal solution for macro-mobility support and slow-moving mobile nodes, but it has limitations in the micro-mobility environment with frequent handoff and high-speed movement of mobile nodes, which requires sending a registration message for each handoff to a possibly distant HA, which increases handoff latency and load on the global Internet. Many solutions have been developed to efficiently support local mobility inside IP wireless networks, such as Cellular IP, HAWAII, and HMIP, which are called IP micro-mobility protocols. IP micro-mobility protocols [3] are proposed to overcome Mobile IP drawbacks. They aim to support fast handoff with minimum packet loss and to minimize signaling overhead. There are a number of issues that motivate the design of IP micro-mobility protocols: fast handoff, IP paging, fast security/AAA services, and quality of service (QOS) support. IP micro-mobility protocols are designed to manage local movement (within the domain) of mobile nodes without interaction with the HAs. This leads to a decrease in handoff delay and packet loss during handoff and a reduction of the signaling load experienced by Mobile IP registration in core networks, so that the wireless access network can scale a very large number of mobile subscribers. The IP micro-mobility protocols can also interwork with Mobile IP to handle movement between domains.

Due to the trend in fourth generation (4G) wireless networks towards All-IP networks, and the drawbacks of Mobile IP and the advantages of IP micro-mobility protocols, and due to the drawbacks and limitations of the surveyed integration solutions, we present a framework for integrating cellular IP access network and MANETs. The integration in such a way supports MANET nodes mobility between different nonoverlapping and overlapping MANETs with multiple gateways, and due to mobility between different nonoverlapping and overlapping MANETs and between multiple gateways, fast handoff is very necessary and important to decrease packet



■ **Figure 11.** *Integrated network architecture.*

loss and service disruption for the MANET nodes. The proposed framework works with any Cellular IP or AODV version. The proposed framework is totally transparent to the MANET mobile nodes because it uses tunneling for packet transmission to the base station. The proposed framework supports many different routing scenarios, as described in [60].

The Cellular IP protocol, described above, is one of the prominent solutions for IP micro-mobility support. It is developed to handle the mobile node mobility within the administrative domain of the wireless access network. The Cellular IP protocol intends to provide local mobility (within the domain) and interworks with Mobile IP in order to provide macro-mobility support (between domains). The protocol supports fast handoff and paging techniques. Micro-mobility support in a Cellular IP network is a more important issue than in the other micro-mobility protocols; due to its simplicity, Cellular IP can efficiently support hundreds of thousands of mobile nodes in a small local area network. Therefore, Cellular IP has been chosen for our integration architecture and protocol. We believe that the integration of MANETs with IP micro-mobility protocols is a better solution than integration of MANETs with Mobile IP for mobility in the micro-mobility environment, such that the advantages of IP micro-mobility protocols can be employed to support MANET mobile nodes fast mobility and handoff.

INTEGRATED NETWORK ARCHITECTURE

The proposed integrated network architecture, depicted in Fig. 11., consists of:

- Multiple overlaid and nonoverlaid MANETs
- Access points, which are Cellular IP base stationss that run the AODV routing protocol on the wireless interface and are connected using a wire link to other Cellular IP nodes and the Cellular IP gateway
- Cellular IP nodes and a Cellular IP gateway, which are used to establish forwarding entries for mobile nodes and forward data packet from/to the Internet
- Mobile nodes (MNs), which use their IP home address for all communication with the Internet

PROTOCOL DESIGN

In the following, a description of the protocol design issues and some algorithmic details of the proposed integrated routing protocol are presented.

Periodic Beacon Signal Message — In this framework, base stations periodically announce their presence on the MANET through broadcasting beacon signal messages. When a mobile node receives a beacon signal, if it is not interested in Internet connectivity, it simply rebroadcasts the beacon signal message to its neighbor nodes. If a mobile node wants Internet access, it extracts the address of base station and the beacon signal sequence number, and saves them in a list of base stations. The mobile node should send an encapsulated route update and page update messages to the base station. Every mobile node should rebroadcast the beacon signal message to its neighboring nodes, and so on. In the proposed integrated protocol, the beacon signal should flood to all mobile nodes in MANET. The time-to-live (TTL) field should be set to the maximum diameter of the MANET. In the proposed protocol, it is assumed that at least one mobile node should be located in the base station coverage area, in order to broadcast the received beacon signal messages to other mobile nodes in the MANET. The base station IP address and beacon signal sequence number are used for preventing reprocessing and rebroadcasting of duplicate beacon signals. It is also used for locating new base stations and creating a default route entry in mobile nodes for the selected base station. When a mobile node receives a beacon signal message, it checks the beacon message IP address and sequence number. If the beacon signal message is received, the mobile node concludes that the beacon signal message is a duplicated message and it discards it.

Route Discovery and Transmission of Packets — It is assumed that mobile nodes in an ad hoc network that want Internet access use their home addresses for all communication with the base station and gateway node in cellular IP access network. The base station should run the AODV routing protocol in its wireless interface. When a mobile node wants to send data packets to a destination address, it uses a route discovery procedure of the AODV routing protocol to search for that destination address. If the destination is found in the ad hoc network, the mobile node sends data packets according to the AODV routing protocol. If the destination is not found, the mobile node concludes that the destination host is not in MANET, and performs a routing table lookup for the IP address of the base station according to default route entry and tunnels data packets to the base station. The base station decapsulates these packets and sends them to the uplink port towards the gateway node. Then, the gateway node sends these packets to the destination node according to its routing table. The destination node may be a node in the Internet or a node in another MANET in the same Cellular IP access network.

Before the mobile node can tunnel data packets to the base station, it should establish the routing entries in the routing cache of each Cellular IP node in the path from the base station to the gateway node. The mobile node should send an encapsulated route update message to base station according to the default route.

Route Update and Page Update Messages — Mobile nodes in the proposed integrated protocol use the same routing update and page update procedures used in the ordinary Cellular IP protocol to establish the routing entries in the routing cache of each Cellular IP node in the path from the base station to the gateway node, with the exception that the route update messages and page update messages may have to traverse multiple hops before reaching the base station. The proposed integrated protocol tunnels route update and page update messages to the base station, and forwards these messages based on the AODV routing protocol.

Movement Detection and Multiple Base Stations — In ordinary Cellular IP access networks, only mobile nodes in the coverage area of the base station can receive a beacon signal message. If the mobile node receives a beacon signal from another base station, it immediately decides to initiate a handoff. This movement detection is called Eager Cell Switching (ECS) [1]. In the integrated protocol, there can be multiple hops between a mobile node and the base station. MANETs can be overlapped, such that there is no clear boundary between these MANETs, and the mobile node can receive beacon signal messages from more than one base station. Therefore, the movement detection algorithm used in the ordinary Cellular IP cannot be used in the proposed protocol. Another movement detection algorithm has been used. The movement detection used in the proposed protocol is based on the hop count from the base station to the mobile node, such that the mobile node can decide whether or not to change its base station. The mobile node should change its base station and initiate handoff to new base station if the number of hops to the new base station is less than number of hops to old base station. The hop count can be obtained from the beacon signal messages recorded in the base station list in the mobile node. Another situation, where the mobile node can detect the move and change its base station and initiate the handoff, when the mobile node misses two consecutive beacon signal intervals form the current base station, or the route to old base station becomes invalid due to mobility or route expiration.

Handoff Algorithms — A modification to the ordinary Cellular IP handoff schemes is proposed for the proposed protocol. Modified hard handoff (MHH) is used when a mobile node moves from one MANET to another, and these MANETs are not overlapped. Also, hard handoff can be used when the mobile node loses the connection with the old base station or the route to the old base station becomes invalid. Modified semi-soft handoff (MSH) is used when a mobile node moves between overlapped MANETs and the hop count to the new base station is less than the hop count to the old base station.

Conclusion

A fixed infrastructure network and mobile ad hoc networks (MANETs) can be combined to make them work together in order to set up a multihop path between MANET nodes and fixed infrastructure base stations, and allow MANET to obtain Internet connectivity. Integrating a fixed infrastructure network with a MANET provides many advantages for both the infrastructure network and the MANET network together. The MANET nodes can access the Internet and access a wide range of Internet services. MANET nodes can move to different MANETs without losing the connection. The fixed infrastructure network can be extended to include dead zones and cover long areas. The number of base stations (access points) can be decreased.

This article has presented a comprehensive survey of solutions for integrating MANETs with the Internet using IP mobility protocols. Several integration solutions have been investigated and their limitations have also been dealt with. A comparison of several integration solutions has been conducted based on metrics such as the type of MANET routing protocol, mobility management type, Gateway discovery, the packet transmission method, agent advertisement, and the movement detection method.

We have observed that some proposals have tried to support micro-mobility by integrating Mobile IP with MANETs, and only one of them has tried to utilize the advantages of the IP micro-mobility protocol. Also, the trend towards all-IP networks enforces the integration of MANETs with micro-mobility access networks, so that more research work is required. In this article, we point out the motivations for the design efficient integration architecture for the micro-mobility environment. A framework for integrating Cellular IP access network and MANETs is proposed. We believe that this approach is a better approach for mobility management with in domain. For future work, the proposed framework should be implemented and studied with different routing scenarios.

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