
A multi-gateway-based architecture for integrating ad hoc networks with the internet using multiple Foreign Agents

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Abstract: Mobile Ad hoc Networks (MANETs) are typically considered to be stand-alone autonomous networks that support multi-hop communication without relying on an existing infrastructure. The integration of MANETs and the internet extends network coverage and facilitates hybrid wired and wireless networking. Most earlier approaches, for integrating MANETs with the internet considered fixed gateways and registration by means of a single gateway or Foreign Agent (FA) with unidirectional connectivity. In this paper, we propose an architecture for integrating MANETs and the internet using multiple Mobile Gateways (MGs) and FAs. MGs move within a one-hop or two-hop distance from the FAs. We extended the Ad hoc On Demand Distance Vector (AODV) routing protocol and Mobile IP (MIP) to achieve the integration. The simulation results show that the use of multiple MGs and a hybrid gate discovery mechanism enhances network performance while providing bi-directional internet connectivity in a multiple foreign agent environment.

Keywords: ad hoc networks; integrated networks; wireless networks; Mobile Gateways; MGs; mobile networks.

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1 Introduction

Advances in wireless communication technologies and the availability of portable computing devices have dramatically increased the demand for pervasive computing and communications. In a stand-alone MANET, network communication is limited to the scope of the network when no external communication is available. Many practical applications, however, require sharing information with external networks, either through wired or wireless links. Several approaches have been recently proposed (Jonsson et al., 2000; Denko and Wei, 2005; Ammari and El-Rewini, 2004; Ahlund and Zaslavsky, 2003; Belding-Royer et al.,

2001; Tseng et al., 2003; Sun et al., 2002; Ratanchandani and Kravets, 2003; Lei and Perkins, 1997) for facilitating communication between MANETs and the internet. Most of the proposed solutions require the introduction of gateways, but the solutions differ in their design architectures, the functionality of the proposed gateways and the routing and communication protocols used for routing in MANETs and the internet domains. These schemes do not allow flexible and multiple connections to access points with MGs, which would give a node the opportunity to choose the most suitable access point when there are network failures or performance degradations.

These proposals consider MANETs as access networks to the internet and provide only unidirectional internet connectivity. They also do not consider multiple MGs and FAs and hence lack mechanisms for load balancing and communication reliability. A notable proposal for load balancing is presented in Huang et al. (2004). However, this work focuses on fixed gateways, although the idea can be extended to the mobile gateway-based architecture.

The Network Address Translator (NAT) and MIP (Perkins, 1997; Huang et al., 2004) are among the commonly used approaches for integrating MANETs with the internet. In Lei and Perkins (1997), a mechanism that uses the Routing Information Protocol (RIP) was proposed for integrating ad hoc networks with the internet. In Jonsson et al. (2000), an architecture called MIPMANET, which uses a MIP foreign agent and AODV (Perkins, 2003), was proposed. MIPMANET allows a visiting node to switch from its current FA to a new FA only if it is at least two-hops closer to the new one. In Tseng et al. (2003), an integration architecture that allows a gateway to decide the Time To Live (TTL) value for packet propagation was proposed. The scope of each MANET is determined by its own TTL value. In Ratanchandani and Kravets (2003), a hybrid gateway discovery scheme that uses MIP to provide global internet connectivity to a MANET in a fixed gateway environment is proposed. The scheme requires nodes to perform route discovery for the gateway when they want to send traffic to destinations on the internet. The hybrid scheme benefits from the combined use of reactive and proactive approaches.

In Sun et al. (2002), an architecture for global internet connectivity with a MIP (Perkins, 1997) extension using AODV is proposed. The selection of FA is made based on the hop count between the FA and the MN. However, hop count alone is not an efficient way of choosing which FA to register with, since network load is not considered. A multihomed MIP that relies on fixed gateways is presented in Wakikawa et al. (2003), which discusses how MNs register with FAs in different multiple-FA environments. In Xie and Kumar (2004), a framework that supports full bi-directional internet connectivity is proposed. It uses an enhanced Destination Sequenced Distance Vector (DSDV) routing protocol as an ad hoc routing protocol and FAs as MIP proxies. However, the gateways are fixed. Due to dynamic network topology, future global wireless internet connectivity must be able to use not only fixed gateways, but also MG, such as those found in vehicular applications.

Recently, schemes that use MGs have been introduced in Denko and Wei (2005) and Ammari and El-Rewini (2004). In Denko and Wei (2005), an architecture that supports bi-directional internet connectivity with MGs and periodic agent advertisement interval was proposed. Its performance in a hybrid gateway discovery mechanism with fixed TTL as a broadcast range was studied. However, internet connectivity via multiple FAs

and a two-hop mobile gateway architecture was not considered. In Ammari and El-Rewini (2004), a three-tier architecture with mobile gateway between nodes within ad-hoc networks and the internet was proposed. In that proposal, the MANET is considered to be an access network and table-driven routing protocol (DSDV) is used for routing in the MANET. Also, both FAs and MGs broadcast agent advertisements to indicate their availability. The MN can register with MGs only if the MGs has already registered with a FA.

In this paper, we propose and evaluate an architecture for integrating MANETs with the internet, using multiple MGs and FAs. The architecture supports registration with multiple MGs and FAs and allows bi-directional internet to MANET connectivity. This architecture ensures reliable connectivity, regardless of node mobility or link failure. The distinctive features of our proposal are the integration of mobile gateway architecture with hybrid agent advertisement and gateway discovery schemes. There are several specific contributions. First, we propose an architecture that supports bi-directional communication. It provides global communication between MANETs and the internet using MGs and FAs. The MGs are selected from MANET nodes based on weighted criteria that consider load, hop count and delay. Second, we consider multiple gateways and maintain multiple routes to gateways to provide load balancing and improve connection reliability. Third, we integrate a hybrid gateway discovery mechanism that dynamically updates the TTL value to maximise packet delivery ratio while reducing communication overheads. Fourth, the architecture supports hybrid agent advertisement and multiple gateway connectivity to FAs.

There are several main differences between the scheme proposed in Ammari and El-Rewini (2004) and ours. In our scheme, a mobile gateway is not required to register with a FA before accepting a registration request from a MN. It can register with a FA after receiving a registration request. Both AODV and MIP are extended to support the mobile gateway architecture. We use a weighted metric to select the best or a set of FAs and MGs. Our proposal supports bi-directional internet connectivity and multiple paths to MGs. A mobile gateway can register with one or more FAs. Our scheme integrates the hybrid gateway discovery and agent advertisement mechanisms.

The remainder of this paper is organised as follows: The next section, Section 2, provides a description of the proposed multi-gateway architecture with single FAs. Section 3 provides a description of the proposed multi-gateway architecture with multiple FAs. Section 4 discusses communication scenarios, addressing and packet routing in the integrated network. Section 5 discusses the results of the performance evaluation for multiple MGs and a single FA-based architecture. Section 6 discusses the results of performance evaluation for multiple mobile gateway and multiple FA-based architectures. Finally, Section 7 presents conclusions and future work.

2 Multiple Mobile Gateways (MGs) with a single Foreign Agent (FA)

2.1 The network model and assumptions

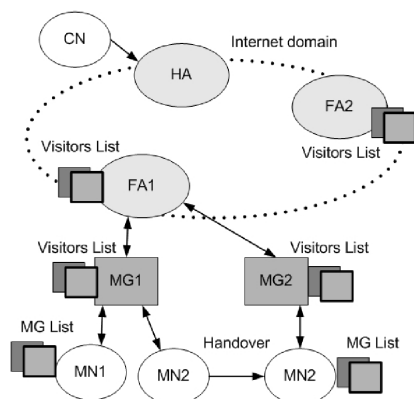
We consider a network with MNs, roaming in a heterogeneous networking environment consisting of MANET and the internet nodes. Nodes within the transmission range form one-hop neighbours while nodes that require one intermediate node to be able to communicate form two-hop neighbours. We assume that each node has a wireless interface that operates in promiscuous mode. Each node can remain in the same MANET or roam between multiple MANETs through the internet. MANET nodes are connected to the internet through the special kind of intermediate nodes called MGs. MNs are at least two-hops away from the internet.

2.2 The architecture and functionality

Unlike existing architectures, which consider MANET to be an access network to the internet, we propose an architecture that supports global and bi-directional connectivity between MANETs and the internet. We use MGs to extend the coverage of MIP agents. The main challenge in MG management is how to reduce overhead in maintaining multi-hop paths and reduce packet losses in the presence of a frequent location changes.

Figure 1 shows the components of the proposed architecture, which consists of MGs, MIP FAs, MNs and Correspondent Nodes (CNs). The figure also shows the handover of MN from MG1 to MG2 while maintaining connectivity to the same FA. The CNs can be static or mobile. In this paper, the terms ‘mobile node’ and ‘MANET nodes’ are used interchangeably. The MG is a MN that connects to the FA in one or two-hops. Other MNs reach the MG over multiple hops. The MIP was designed to support one-hop communication and uses proactive messages for location and address management. On the other hand, ad hoc on-demand routing protocols operate reactively. To use both protocols, we extended the MIP and the AODV (Perkins, 2003) protocols. The MG runs extended the AODV and MIP protocols to support mobility management, handover and hybrid gateway discovery.

Figure 1 Example architecture for multiple MGs and a FA registration



2.3 The significance of mobile MGs

Most existing architectures use fixed gateways to interconnect MANET with the internet. Moving gateways are needed in application scenarios for computers deployed on military vehicles in battlefield communication, emergency relief coordination centres in disaster recovery and search and rescue operations in law enforcement. The MGs permit the MN to maintain connectivity, with added flexibility in the presence of node mobility. In static gateways, however, access to the gateway is limited with a fixed radio range, while MGs' movement between MANET and FA facilitates better accessibility.

2.4 Extended protocols for facilitating the integrated architecture

We have extended MIP and the AODV routing protocol to support the proposed architecture. MIP has been extended to allow MNs to interoperate with MGs and register with multiple FAs. It allows for the registration and maintenance of connectivity of mobility agents. By integrating ad hoc networks and wired IP networks using MIP for mobility management, multiple paths to the gateways are maintained, enhancing network support for MNs.

The AODV protocol is extended to create and maintain the route entry based on MIP messages, so that it can improve network performance through sharing MIP messages. The AODV protocol is aware of visitors registered with the MG. For destinations within MANET (MANET nodes or visiting CN), AODV is used. For destinations outside MANET, the foreign network or MANET domain, or the internet, extended AODV/MIP is used.

2.5 The agent advertisements

Communication between FAs and MGs can be reactive or proactive. The MIP FAs broadcast agent advertisement to reachable MGs. A MG that has not registered with another foreign agent, or whose registration lifetime has expired, sends registration request messages to a foreign agent. Each registration has a lifetime and a MG can register with the same or different FA after the expiration time.

In addition, MGs can broadcast solicitation messages to learn the availability of FAs. In such cases, a foreign agent that receives the message unicasts the FA advertisement to the MG. The MG also sends advertisement message to MNs. The advertisement message contains information such as registration lifetime, the IP address of the MG and MG load in a route reply packet. If a new MANET node seeks internet connectivity, it discovers the MG.

We consider two types of advertisements: periodic and adaptive. A periodic advertisement is made at a fixed time interval. Longer intervals cause less overhead than shorter intervals. In periodic advertisement scheme, all gateways initiate the advertisement at the same time. To achieve time synchronisation among MGs, we adapted the scheme proposed in Cao and Welch (2004). The scheme reduces

the chance that the advertisements from neighbouring MGs reach the same nodes by travelling the same hop counts. However, tight synchronisation is difficult to achieve in real MANET application scenarios. The adaptive advertisement is carried out only when changes are detected. Changes are detected upon receiving or generating a route error message.

We use a hybrid of periodic and adaptive schemes, which operates as follows. When no events are detected during the specified period, the adaptive scheme will be used. When the topological changes occur at a longer period than the length of the periodic changes, an adaptive scheme will be used. However, when events occur within the period, only the periodic scheme will be used. The advantage of such a scheme is that the overhead in sending advertisements too frequently is reduced. The overhead brought about by periodic advertisement in the absence of changes is also avoided.

2.6 Registration with multiple MGs

FAs use MGs as the first intermediate node to establish communication with MNs. While MNs that are located one-hop away from the MGs can directly communicate with MGs, MNs that are more than one-hop away, use multi-hop routing scheme for routing and packet forwarding. MNs can locate multiple MGs either by solicitation or by detecting the advertisements. They can register with new MGs or update their routes to existing MGs when they find shorter routing paths. If the route is already available in the routing table, it is then refreshed. If a MANET node registers with multiple MGs when it roams in an overlapping area, the FA receives multiple registrations of this node through the MGs. In our proposal, if a MN wishes to initiate communication with an internet node, it sends a registration request to the MG and registers with it. The MG in turn registers with the FA, if it did not previously register with the FA and allows communication with the internet. In general, MGs make the registration request with FAs either before or after receiving internet connectivity request from MNs. When a new MN visits MANET, it registers with the nearest MG. This MG then forwards list of visiting nodes to other MGs in the same MANET. This helps in avoiding external route search when communication with recently joined MN desired.

2.7 Selection of a mobile MG

Most existing architectures proposed to support MANET and internet connectivity are based on a default gateway configuration and support a single gateway. In our proposal, we consider the use of multiple MGs. To be selected as a MG, a node should be one-hop away from the FAs. When there are multiple reachable MGs, the selection of a suitable gateway is made based on a weighted criterion that uses hop length, delay and load. The delay is measured using TTL, as described in Ahlund and Zaslavsky (2003) and load is measured using the number of MNs that the FA is serving.

The MN maintains multiple MGs and multiple paths to them, based on weighted criteria. To achieve this goal for each MG, a MN maintains the combined metric, as follows:

$$W_n = w_1\rho + w_2\lambda + w_3\delta, \quad w_1 + w_2 + w_3 = 1 \quad (1)$$

where ρ , λ and δ are system parameters representing the load, delay and hop length respectively. The variables w_1 , w_2 and w_3 represent the weights for the corresponding parameters. The first component of the combined metric, $w_1\rho$, takes the effect of gateway load into account. A MG with a lower load is preferred for selection. The second component of the combined metric, $w_2\lambda$, provides the contribution of hop length to the combined metric. A MG with shorter hop lengths to a node is chosen. The last component, $w_3\delta$, provides the contribution of delay to the combined metric. A MG with lower delay is preferred for better performance. In a combined metric scenario, a MG or set of MGs with lower W_n is selected as the MG with which to register. The contribution of each weight can be varied according to network conditions.

2.8 Selection of a FA

Agent advertisement messages from the FA are sent to the MGs. The advertisement message contains similar information broadcasted by the MG, as well as additional information, such as the number of nodes it is currently serving. If an MG can reach multiple FAs, it will register with one based on the weighted criteria and can update its selection based on the agent advertisement later.

If registration is possible with multiple FAs, the selection of a suitable FA is made based on combined load and delay criteria. For this purpose, a MG maintains the combined metric:

$$C_n = c_1\rho + c_2\delta, \quad c_1 + c_2 = 1 \quad (2)$$

where ρ and δ are system parameters representing load and delay respectively. The variables c_1 and c_2 are the weights for the corresponding parameters. The first component of C_n shows the effect of load on FA selection, while the second component shows the effect of delay. Using the combined metric, C_n , a FA or a set of FAs with the lowest C_n is selected.

2.9 Mobile gateway discovery

The performance of the MANET when integrated with the internet depends on the strategies used for gateway selection and discovery. Most existing schemes use either proactive discovery or reactive discovery mechanisms for integrated networks using fixed gateways. In the proactive discovery mechanism, the gateway periodically broadcasts the agent advertisement to other nodes in the network. Any MN that wants to interact with the internet nodes detects this packet and begins registration.

In reactive gateway discovery, a MN initiates the gateway discovery. The proactive discovery mechanism reduces the average delay compared to reactive discovery,

but incurs a higher communication overhead. A hybrid gateway discovery scheme is suitable, since it uses the best features of the reactive and proactive discovery strategies.

There are two approaches for a hybrid gateway discovery scheme involving TTL. In hybrid scheme with fixed TTL, the MG broadcasts its availability to k -hop neighbours or broadcast zones. The advertisement packet contains the MG IP address, expected lifetime, number of registered nodes, a sequence number and hop length to the FA. Nodes that are not reachable by the MG broadcast to find the nearest MG using the reactive discovery mechanism. This scheme is an attempt to reduce communication overhead, as not all MNs want internet connectivity.

In hybrid scheme with adaptive TTL, an adaptive mechanism overcomes the problem of fixed TTL value to define a broadcast zone. Threshold values are used to adapt to either of the protocols (reactive or proactive) based on topological changes. These changes may be due to neighbourhood change or route change caused by node mobility or wireless link failure. A higher value of TTL is used when the topology change is low, since the information can last longer. The advantage of this scheme is that the TTL values can be changed dynamically to favour reactive or proactive schemes dynamically. In our work, we use hybrid gateway discovery mechanisms with adaptive broadcast zone.

3 Multiple gateways and FAs

3.1 Description of the proposed architecture

In order to establish flexible and reliable global communication, multiple network connections for MNs would be required in future applications. For this purpose, we propose a two-hop gateway architecture, in which MGs can be at most two-hops away from the FA. The use of the two-hop gateway and the availability of multiple gateways provide reliability, robustness and flexibility. In this architecture, we will compare the effect of gateway mobility using the Random Waypoint model and optimal placement algorithm, with constraints on physical boundaries and obstacles in the area.

As in the preceding section, the proposed architecture involves MNs, MGs, internet nodes and FAs, with provisions for the registration with multiple FAs. MGs play an intermediary role between MANET nodes and the internet. The MNs register with MGs, and MGs in turn register with FAs. Connectivity information is maintained between each of these entities to provide reliable communication in spite of node and gateway mobility. In the following section, we will discuss how a MN registers with multiple FAs.

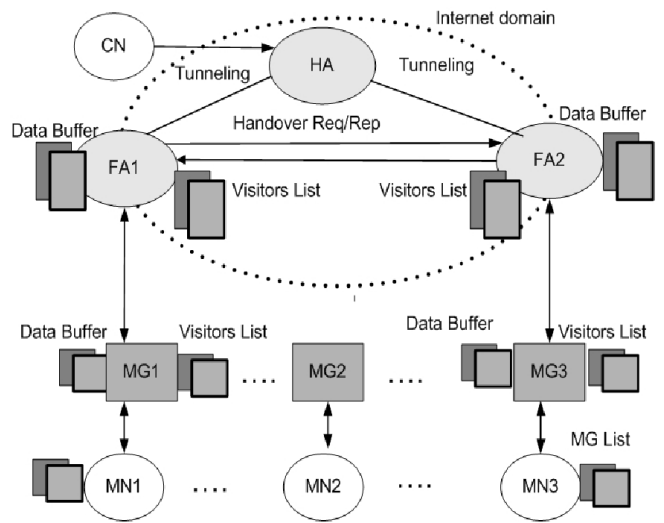
3.2 Registration with multiple FAs

To improve the reliability of connections, multiple FA addresses are maintained. This can help by adding robustness to changes in network topology. In multiple-FA-based MANETs, if the MN registers with multiple FAs simultaneously, the home agent will have multiple bindings for one MN in its binding table. Different mechanisms exist in the literature for computing a metric to choose a suitable FA. In Ahlund and Zaslavsky (2003), the Jacobson-Karel algorithm (Peterson and Davie, 2000) is applied to determine the metrics used for selecting a care-of address.

In our proposal, a MG chooses to use an FA based on weighted criteria. The delay between the home agent and the MN is computed based on the registration messages sent between the MN and the home agent. Therefore, the home agent will handle the entire registration process for the MN and will record the delay to the binding table for its next registration.

Figure 2 shows the proposed architecture for registering with multiple FAs. The MGs register with the FAs and the MNs register with the MGs. The figure shows a scenario where MN1, MN2 and MN3 register with MG1, MG2 and MG3 respectively to gain internet connectivity through two different FAs. The MN chooses one or more MGs based on the selection criteria. Once the gateway is selected, data is sent through this gateway to the internet hosts if the destination is not in the local network. The network prefix of the currently connected FA is used to decide whether the destination is in the MANET or on the internet. Handover between the FAs is performed when a MN moves from one FA domain to another domain by initiating a handover request and reply mechanism.

Figure 2 Example architecture for multiple MGs and multiple FAs registrations



If the internet node wishes to send packets to a MN that has moved to another MANET, it will send them to the MN's home network. The home agent, having multiple bindings for the MN's home address, might select the FA with the best metric as discussed in Section 2.8.

3.3 Placement of mobile gateway

3.3.1 Optimal gateway placement

Two scenarios were considered for gateway mobility. In one scenario, the MG moves according to the Random Waypoint model, but with a lower speed than ordinary nodes. In another scenario, the MG moves according to optimal placement, based on a trajectory update algorithm with weighting factors of load and delay. We use the weighted criteria specified in equation (3).

For n MNs, the optimisation problem that takes boundary and blockages into account is formulated as follows (Ahmed et al., 2001):

$$\begin{aligned} \min \sum_{i=1}^n f(\delta_i, \rho_i) \cdot |x_0 - x_i| \\ \text{subject to } w_1 \leq x_0 \leq w_2 \\ x_0 \leq b_{1k} \\ x_0 \geq b_{2k}. \end{aligned} \quad (3)$$

The x_i 's represent the coordinate vectors of the MN and x_0 is a position vector representing the expected gateway position. Both x_0 and x_i are measured with reference to a suitable origin of interest. Our weighting factor is a function that depends on the i th node's load and delay. The variables w_i and b_{ik} are location vectors representing the rectangle covering the domain and the boundary of the k th blockage respectively. We considered different weights in our simulation. Equation (3) minimises the sum of the weighted distance from the mobile gateway to the MNs, subject to the boundary and blockage conditions.

Unlike the scheme based on the Random Waypoint model, the MG executes the trajectory update algorithm within a predefined interval, which involves the following steps.

- 1 Input data needed for computing optimal MG positions within two-hop ranges.
- 2 While there is data to be sent, collect position information of the nodes at each sampling interval.
- 3 Collect the load and delay information for each node.
- 4 Compute optimal locations and move to optimal position subject to boundary and blockage constraints.
- 5 Continue while nodes have data to send by repeating the same procedure at the next sampling interval.

3.3.2 Random movement

To simulate random mobility, the Random Waypoint model (Broch et al., 1999) was used. The main steps involved are described as follows:

- 1 Choose initial position p (within the network area).
- 2 Choose a random destination d .
- 3 Move to the random destination at a random speed uniformly chosen from $[V_{\min}, V_{\max}]$, where V_{\min} and V_{\max} are the minimum and maximum speed used in the simulation.
- 4 Wait for n seconds (typically a constant, could be a random variable).
- 5 While not end of the simulation, repeat from Step 2.

The gateway selection and registration process is carried out as discussed in Section 2 in a one-hop MG scenario.

4 Global communication scenarios

The MG maintains a list of internal nodes and visiting MNs. MGs exchange information about all visiting MNs and the MANET nodes currently being served by them. A visiting MN can choose a particular MANET based on its proximity. A visiting node can be from another MANET or just a visiting MN; both consider the current network as their FAs and accessible via the gateway they registered with. Packets are exchanged between the internet and MANET nodes using a combination of three kinds of routing schemes: traditional IP routing, MIP routing and AODV-based ad hoc routing, as described in the following section.

4.1 MANET-internet communication

When the static internet node wishes to communicate with the MANET, it uses the IP routing in the internet, MIP routing between the FAs and MGs and the AODV protocol within MANETs. When a MANET node wishes to communicate with the internet, the packet is forwarded to the gateway, which in turn forwards it to the FA.

A MANET node may also move from its home network to another MANET and register with the MG in new MANET. After the MN has finished the registration process, all packets destined to it will be encapsulated by the home agent and forwarded to the hosting foreign agent. When they reach the destination network, they are decapsulated by the foreign agent and delivered to the destination through the serving MG.

Incoming packets from the internet are delivered to MANETs if the destination is at home or forwarded to the MG and tunnelled to the destination network if

the destination is not on the network. All packets destined to destinations outside the local MANET are routed along the MGs and delivered to the corresponding FAs for further processing.

4.2 Addressing and packets processing

In our proposal, two types of mobility are considered. The first type of mobility involves mobility within a MANET, where a node moves within the scope of the same or different MGs. The second type of mobility involves mobility between MANETs and CN over the internet. This type of mobility communication can include MANETs or MANET and CN, both being located across the internet. The communication involves both local and global addressing. After a MG has registered with a FA, local addresses are used for intra-MANET communication.

All MANET nodes use the same addressing type. We assume that both MNs and MGs have a globally routable IP address used for a node to communicate with external nodes. A globally routable and topologically correct address can be generated using autoconfiguration (Belding-Royer et al., 2001; Perkins, 2001; Jeong et al., 2005).

4.3 Inter-MANET communication

When a communication is intended among independent MANETs that do not rely on the internet, direct communication can be established if they are reachable. In such multiple MANET scenarios, the boundary between them is defined in terms of the hop length from a gateway.

Communication between MANETs when the source and destination nodes are located on two different networks may be desired. Assume that each MANET is connected to the internet and being served by a MG. In this scenario, packets from MNs are transmitted to the MG and foreign agent using AODV and transmitted through the internet using the IP routing until it reaches the foreign agent. From the foreign agent, it will be forwarded to the MG serving the destination MANET, using MIP routing, and finally delivered to the required destination using AODV protocol.

5 Performance evaluation of a one-hop MG architecture

In this section, we will present results of the simulation experiments to evaluate the performance of a multi-gateway and single foreign agent architecture. A hybrid gateway discovery mechanism that adaptively adjusts the value of TTL was used.

5.1 Simulation environment

To evaluate the proposed scheme and compare it to the existing scheme proposed in Ammari and El-Rewini (2004), we carried out simulation experiments using the Network Simulator, NS-2 (McCanne and Floyd, 1997). Three FAs were used per MANET, but a MG could register only with

one FA. The FAs were placed at the centres of the simulation area, facing each other. Up to 50% of the MNs sought internet connectivity. In the simulation, hybrid adaptive gateway discovery based on adaptive TTL was used. The statistics in the simulation were collected 100 s after the start of the simulation to allow for warm-up time and ensure the establishment of routes and registration.

MNs in a MANET move according to the Random Waypoint model (Broch et al., 1999). In the simulation, we used the CBR traffic sources. About 20 CBR sources were used to generate packets at the rate of five packets per second. The simulation parameters are given in Table 1. The MGs and MNs moved at a random speed uniformly chosen from [min, max] ranges.

Table 1 Simulation parameters

<i>Parameters</i>	<i>Default values</i>
Maximum number of MNs	100
Maximum number of MGs	5
Simulation area	1000 m × 1000 m
Transmission range	250 m
Traffic type	CBR
Speed of mobile node (m/s)	0–25
Speed of MGs (m/s)	0–10
Routing protocol	AODV
Length of simulation time	1000 s
Pause time	30 s
Number of simulations	20 runs
Packet size	128 bytes
Registration lifetime	25 s
Beacon time (FA)	10 s
Beacon time (MG)	15 s
Agent advertisement	5–30 s

5.2 Performance metrics

We used four performance metrics; namely, average packet delivery ratio, average mobile gateway overhead, average node-MG connectivity ratio and average gateway lifetime.

- the packet delivery ratio is defined as the ratio of the total number packets received and the total number of packets transmitted
- the mobile gateway overhead is defined as the total number of registrations and agent advertisement messages generated by the mobile gateway during the simulation
- the gateway connectivity ratio is defined as the percentage of time when at least one gateway is reachable by the MNs during the simulation time
- the gateway lifetime is defined as the length of time for which a node had a valid path to the MGs.

The two metrics, gateway connectivity and lifetime, measure the effectiveness of the proposed mobile gateway approach in the integrated network.

5.3 Discussion of simulation results

In this section, we investigate the effects of the number of MGs, the speed of MGs and number of MNs on packet delivery ratio, gateway overhead, gateway lifetime and node-gateway connectivity.

5.3.1 The effect of the number of nodes

Figures 3 and 4 show the effect of number of nodes on the packet delivery ratio and the gateway overhead. Figure 3 shows that when the number of MNs increases, the packet delivery ratio slightly increases and then starts decreasing. The increase in the number of MNs increases the packet delivery ratio due to the availability of more forwarding nodes. However, as the network size becomes much larger, more nodes participate in sending packets, causing more traffic. When the number of MNs increases, a single MG can serve more nodes, resulting in slightly lower packet delivery ratios.

Figure 3 Packet delivery ratio as a function of number of nodes

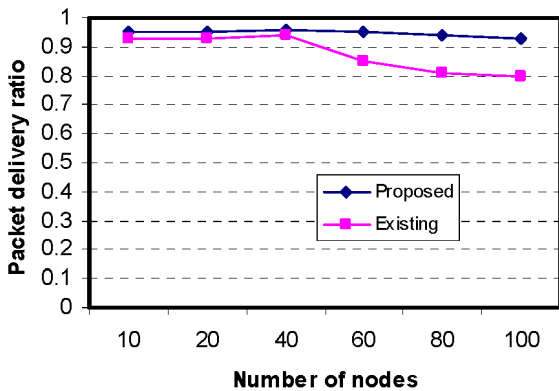
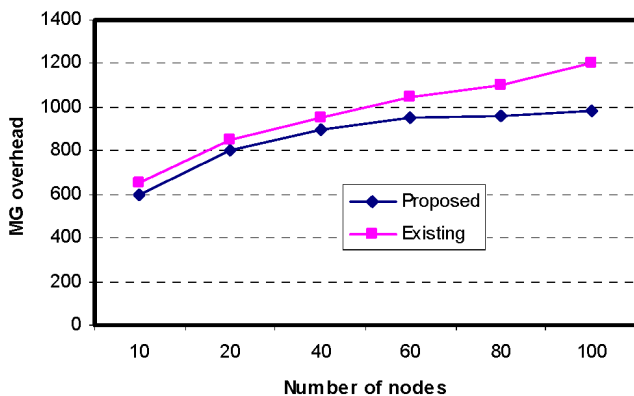


Figure 4 MG overhead as a function of number of node



It was observed that even if the number of nodes increases, only a few of them need internet connection simultaneously. The performance of the proposed scheme was observed to be better than the existing scheme, due to the use of the integrated adaptive gateway discovery scheme and the use of multiple paths. In addition, the use of hybrid periodic and adaptive strategies for advertisement has reduced the overhead, as shown in Figure 4. However, the overhead increases in both schemes when the number of nodes

increases. Thus, as the number of nodes increases, the MG overhead increases slightly. However, using the hybrid advertisement and gateway discovery schemes can improve performance.

5.3.2 The effect of number of Mobile Gateways (MGs)

Figures 5 and 6 show the effect of number of MGs on packet delivery ratio and gateway overhead. Figure 6 shows that when the number of MGs increases, the packet delivery ratio also increases. The presence of multiple MGs and the maintenance of multiple routes to the gateway increase connectivity and packet delivery ratio. It was also observed that an increase in the number of MGs improves performance, since MNs have a higher probability of registering with them. The gateway overhead increases for both schemes, and the difference is not significant with a lower number of MGs.

Figure 5 MG overhead as a function of number of MGs

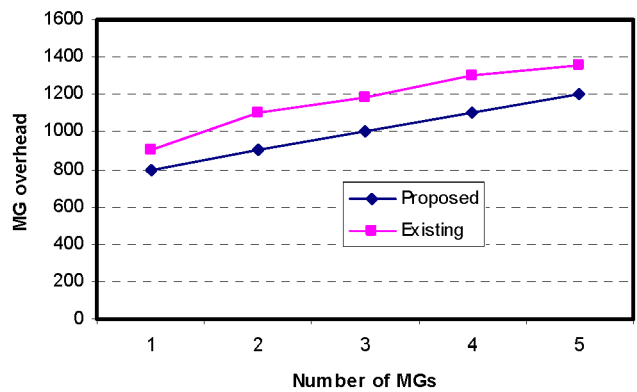
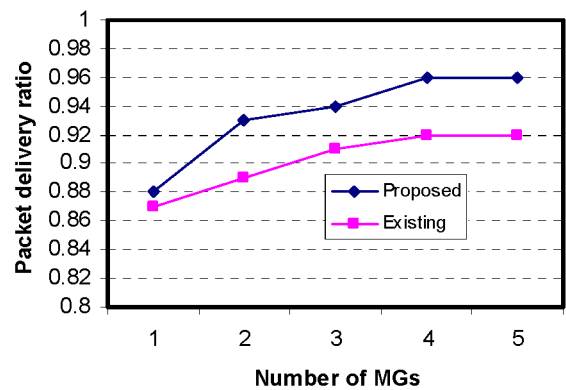


Figure 6 Packet delivery ratio as a function of number of MGs



For the reason of excessive flooding overhead, fewer MGs should be applied if only a few nodes in the MANET require communication with the internet. On the other hand, while increasing the number of gateways can provide a better load-balancing mechanism, agent advertisement traffic can overload the network when it gets much higher. Our approach is better with respect to packet delivery and overhead, due to the adaptive and hybrid gateway discovery and agent advertisement strategies.

5.3.3 The effect of gateway speed

Figures 7–9 show the effect of the average speed of MGs on packet delivery ratio, MG lifetime and node-MG connectivity. Figure 7 shows that the packet delivery ratio decreases slightly with an increase in speed. This occurs because with increases in mobility, packets are lost since MGs lose connectivity to the FA and MNs encounter route changes. However, since a MN registers with multiple MGs and MGs can register with multiple FAs, the effect of MG speeds on packet delivery ratios is not significant.

Figures 8 and 9 show that node-MG connectivity and gateway lifetime also slightly decrease in both schemes, with our proposed scheme performing much better. This occurs because when the speed of MGs increases, more links will be broken, requiring the initiation of a new registration process. However, the effect of the mobility of the gateway on performance is reduced, due to the use of multiple paths and alternative gateways. We carried out experiments with varying pause times, and the results revealed that, in addition to speed, the length of the pause time affects performance. Longer pause times and higher speeds perform better than shorter pause times and higher speeds. The former allows for better packet delivery than the latter. In general, the rate of increase in the delay is higher at relatively higher speeds than lower speeds.

Figure 7 Packet delivery ratio as a function of speed of MGs

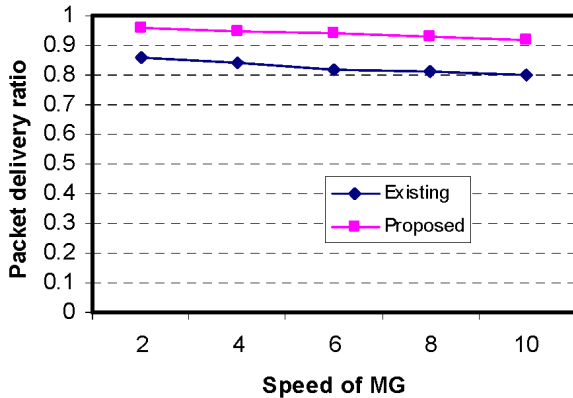


Figure 8 Node and MG connectivity as a function of MGs

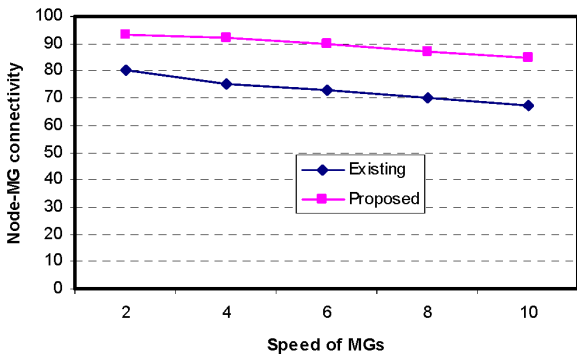
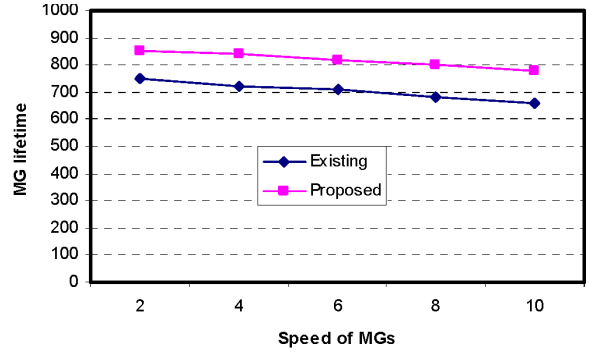


Figure 9 MG lifetime as a function of speed of MGs



6 Performance evaluation of a two-hop MG architecture

In this Section, we will present the results of the performance evaluation on a multi-gateway and multiple foreign agent architecture. MGs can move within the range of two-hops from the FAs. As in Section 5, we used the NS-2 (McCanne and Floyd, 1997) simulation tool.

6.1 Simulation environment

The simulation environment consists of multiple FAs, MANETs and MGs. Each MANET also has two CNs and 100 MN. The nodes were randomly distributed in the network. The proportion of MN that sought internet connectivity varied between 10% and 50%.

The nodes roam between MANETs and the internet according to the Random Waypoint mobility model (Broch et al., 1999). The MGs move according to the Random Waypoint in the first scenario and according to an optimal placement algorithm with trajectory control in the second scenario. As a traffic model, 20 CBR sources were used to generate packets at the rate of five packets per second. The weighting factor of one was used in all experiments. The effects of MG speed, the number of registered nodes and the advertisement interval were investigated. The MGs and MNs moved at a random speed, uniformly chosen from their respective ranges. The simulation parameters are shown in Table 2.

Table 2 Simulation parameters

Parameters	Default values
Maximum number of MNs	100
Maximum number of MGs	5
Number FAs per MANET	3
Simulation area	1000 m × 1000 m
Transmission range	250 m
Traffic type	CBR
Speed of MG (m/s)	0–10

Table 2 Simulation parameters (continued)

Parameters	Default values
Speed of mobile node	0–20
Routing protocol	AODV
Length of simulation time	1000 s
Pause time	30 s
Number of simulations	10 runs
Packet size	128 bytes
Registration lifetime	25 s
Beacon time (FA/MG)	10 s
Beacon time (MG)	15 s
Agent advertisement	5–30 s

6.2 Performance metrics

As in Section 5, we used four metrics to evaluate performance: the packet delivery ratio, gateway overhead, node-gateway connectivity ratio and gateway lifetime. In this simulation, gateway movement follows the Random Waypoint model or optimal placement with trajectory control, in which the MG can roam about two-hops away from the FAs. Gateway discovery follows a hybrid gateway discovery with adaptive broadcast range, using the TTL value.

6.3 Discussion of results

In these simulation experiments, the MNs can move from one MANET to another MANET directly or via the internet. Figures 10–16 present the impact of gateway speed, the number of MNs and number of MGs on the performance metrics under two different gateway movements.

6.3.1 The effect of speed of Mobile Gateways (MGs)

Figures 10–12 show the effect of the average speed of MG gateways on the packet delivery ratio, node-gateway connectivity ratio and gateway lifetime. The change in the speed of MGs affects the network connectivity between the MNs and MGs. This triggers a change in the MGs, resulting in a lower node and gateway connectivity and packet delivery ratio, as shown in Figures 10 and 12.

Figure 10 The packet delivery ratio as a function of speed of MGs

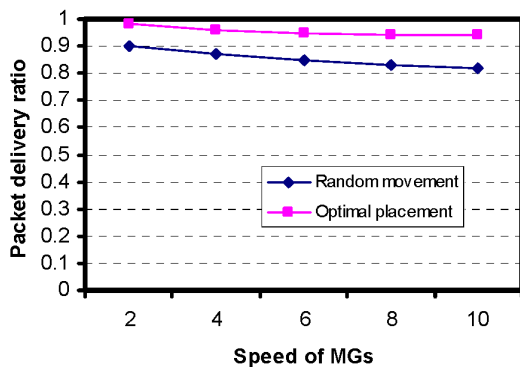


Figure 11 MG lifetime as a function of speed of MGs

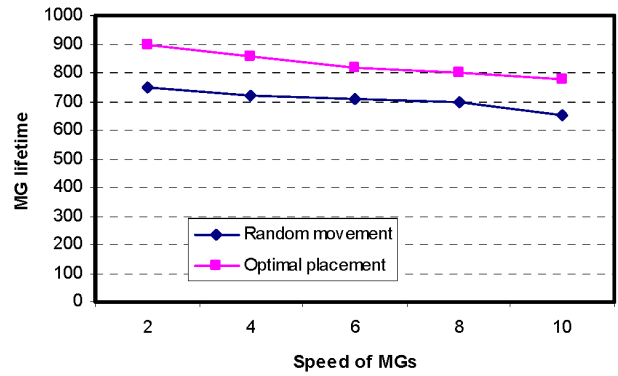


Figure 12 Node and MG connectivity as a function of speed of MGs

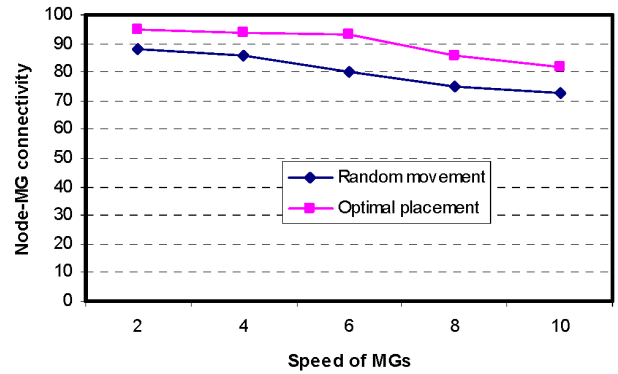


Figure 13 MG overhead as a function of number of nodes

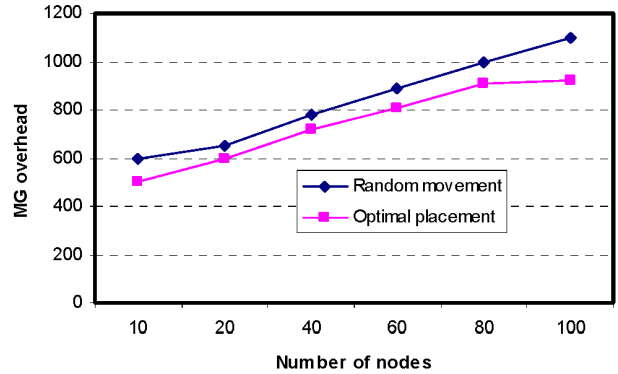


Figure 14 Packet delivery ratio as a function of number nodes

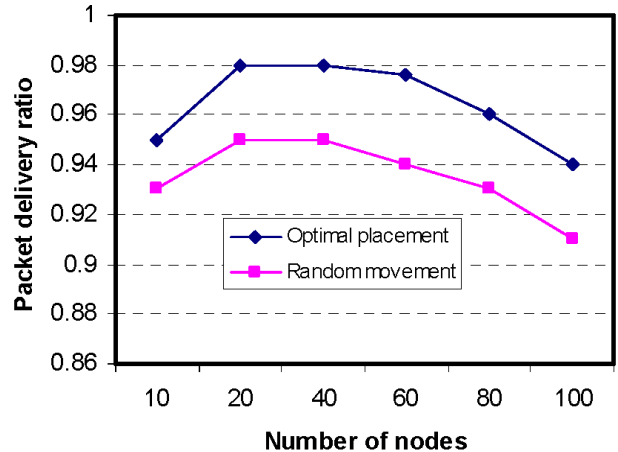
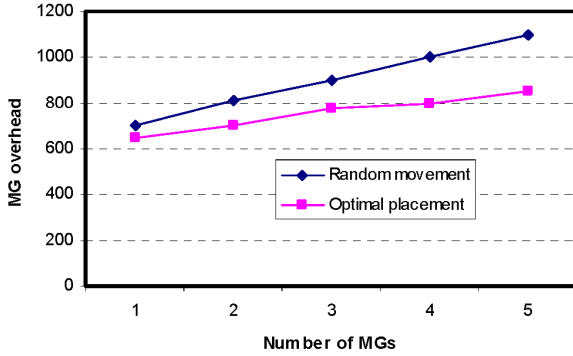
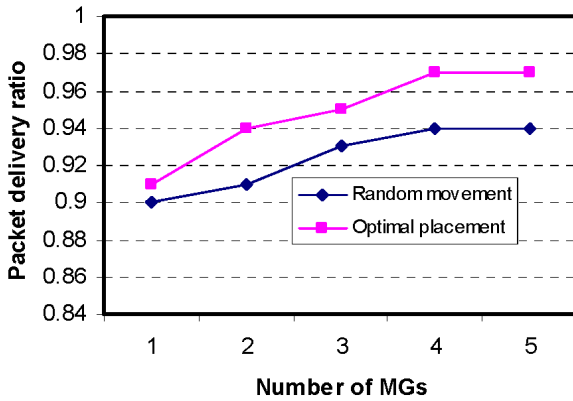


Figure 15 MG overhead as a function of number of MGs**Figure 16** Packet delivery ratio as a function of number of MGs

However, we can see that when the speed of MGs increases, the gateway lifetime decreases slightly, as shown in Figure 11. With multiple MGs available, the MNs can achieve more stable connections, although frequent route maintenance can occur due to changes in speed. In addition, because more FAs participate in the registration service, a home agent can choose the shorter routing path for packet transmission. This allows not only better packet delivery ratios, but also higher node gateway connectivity. Our simulation results demonstrate that the use of the proposed architecture and adaptive gateway discovery mechanism ensures communication performance and provides more reliable communication under an optimal gateway placement strategy.

6.3.2 The effect of the number of nodes

Figures 13 and 14 show the effects of the number of MNs on the packet delivery ratio and mobile gateway overhead. When MNs move from one MANET to another, they can register with multiple MGs, providing connectivity to different FAs. Since not all nodes in a MANET need internet connectivity, the performance degradation is not much higher, as shown in the packet delivery ratio. Figure 14 shows that packet delivery ratio initially increases and then decreases when the number of MNs exceeds 60, in both scenarios. Thus, the increase in the number of MNs also increases the packet delivery ratio up to a maximum network size and then starts declining, due to increased network traffic.

There is a slight difference between the optimal placement and random movement schemes with respect to overhead, as shown in Figure 13, at a lower number of nodes. The difference becomes larger with the increase in number of nodes. There is consistently higher overhead for a gateway that moves based on the Random Waypoint model, due to frequent loss of connectivity, which results in higher numbers of control messages.

6.3.3 The effect of the number of MGs

Figures 15 and 16 show the effect of the number of MGs on packet delivery ratio and gateway overhead. The results show that the optimal gateway placement outperforms the random movement scenario. The packet delivery ratio increases, since there is a greater chance for MNs to register with multiple MGs and for MGs to register with multiple FAs. The difference in the overhead is caused by the random movement, which results in frequent changes and the generation of control messages.

7 Conclusions and future work

In this paper, we have proposed a MG-based architecture for integrating MANETs with the internet, using multiple MGs and FAs. The performance of the proposed architecture and gateway discovery mechanisms was evaluated using simulation. Two sets of simulation experiments were performed. In the first set of simulation experiments, the architecture supporting MG mobility in the vicinity of one-hop from the FAs was investigated. A comparison was made with a similar, existing scheme for one-hop-based architecture. The simulation results show that the effect of the mobility of the gateway on performance was reduced by using multiple paths and alternative gateways. The use of adaptive gateway advertisement and hybrid gateway discovery mechanisms increased the packet delivery ratio and reduced the gateway overhead.

In the second set of simulation experiments, an architecture supporting multiple MGs and FAs was investigated, in which the MG could roam two-hops away from the FAs. Two types of MG mobility scenarios were studied. In the first scenario, MGs moved according to the Random Waypoint model. In the second scenario, the MGs' movement was based on an optimal placement algorithm. The effects on performance under the two gateway movement strategies were investigated. The simulation results show that the movement of gateways following the optimally controlled trajectory algorithm outperformed random movements. The use of multiple gateways and FAs improved performance by providing load balancing and increasing connectivity.

We are currently investigating the effects of various mobility models, such as the social network model (Musolesi et al., 2004) and the group mobility model (Hong et al., 1999), on the performance of the proposed architecture. The scalability of the integration architecture and handover latency will be studied using various traffic

models. We are also planning to evaluate the proposed scheme in the implementation testbed, using real traffic data and analyse the generated data statistically.

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