Hindawi
Wireless Communications and Mobile Computing
Volume 2020, Article ID 8810761, 16 pages
https://doi.org/10.1155/2020/8810761

Research Article

Integrating Mobile Ad Hoc Networks with the Internet Based on OLSR

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Received 10 May 2020; Revised 5 September 2020; Accepted 7 October 2020; Published 23 October 2020

Academic Editor: Liang Dong

Although a standalone and isolated mobile ad hoc network (MANET) is practical in many scenarios, integration with the Internet is much more advantageous. The integration of a MANET with the Internet provides MANET users with Internet access and hence increases the scope of the MANET application. In addition, the Internet can benefit from this integration by an extension of the network coverage area. However, the integration of heterogeneous networks raises many issues. To overcome the incompatibilities between different architectures, gateways are used. This paper proposes a lightweight integration scheme for a MANET and the wider Internet, based on the optimized link state routing (OLSR). OLSR routing messages are reengineered and optimized to meet the needs of integration without involving additional routing messages for gateway discovery. The compulsory registration of a MANET node with a gateway node in a traditional integration is not required in the proposed approach, meaning that nodes can move freely within the local MANET with no disruption in the connection to another node in the external network. The proposed system is evaluated using the OMNET++ network simulator and is compared to another existing system. The simulation results demonstrate the validity of the proposed approach.

1. Introduction

A mobile ad hoc network (MANET) is a type of network that does not require an infrastructure for deployment. It is a collection of isolated mobile nodes that are connected to each other in a self-configurable, infrastructure-less, dynamic, and decentralized network. Mobile nodes are equipped with wireless interfaces that utilize radio channels to communicate with each other, without the need for centralized management. A mobile node in a MANET acts as both an end system and a router to participate in data routing within the network. Generally, routing in MANET is divided into reactive and proactive routing and hybrid schemes that combine features of both groups [1]. Reactive routing is also known as an on-demand routing, where routes between nodes are discovered when needed (e.g., AODV and DSR), while proactive routing involves setting up all routes in advance of their use (e.g., DSDV and optimized link state routing or OLSR).

MANETs have been used in a number of different scenarios. A MANET can be used to set up a network in a disaster area, emergency rescue operation, military battlefield, or forest. However, as a stand-alone network, its areas of application are rare compared with other wireless networks, and the MANET technology is therefore being integrated with other technologies to enhance its usability. A MANET may form part of another communication architecture such as a machine-to-machine network, the Internet of Things, or a wireless cellular network [2].

When integrated with other network technologies, a MANET technology can complement these. Integration reduces the communication and deployment costs and provides additional services to the MANET. The integration of a MANET with an infrastructure network can benefit both networks; for example, integrating a MANET with an IP infrastructure would provide MANET users with Internet access and hence increase the application scope for the MANET. Such a setup would allow MANET users to access web services that are not available in the stand-alone MANET.

Conversely, IP infrastructure networks can benefit from integration with a MANET by extending the coverage area;

for instance, the integration of a cellular network with a MANET expands the network coverage. This integration can allow web services to be accessible from remote areas that are beyond traditional Internet coverage.

The integration of heterogeneous networks unavoidably raises significant research issues, due to the differences in the networking architectures employed. Participating networks in a heterogeneous setup may use different protocol stacks and routing mechanisms [3].

To overcome the incompatibilities between different communication architectures, gateways have often been employed. Gateways act as interfaces to maintain connectivity between heterogeneous networks. A router or mobile node can be a gateway as long as it is equipped with the required technology. Gateways typically support at least two network standards; for instance, a mobile node may use mobile IP to communicate with the worldwide Internet on one side and an ad hoc network routing protocol to communicate with a local MANET on the other.

Despite the fact that gateways have eased the incompatibility issues when integrating heterogeneous networks, they have also raised many challenges. Gateway discovery, gateway selection, and load balancing between existing gateways and overhead management are examples of the challenges when integrating a MANET with the Internet [4–7]. Moreover, security management, micromobility, and handoff are other issues that need to be tackled.

In an integrated MANET-Internet network, a mobile node may frequently move away from its current gateway node. This inevitably results in disruption to the connection between the two end entities from different networks. A participating mobile node in an integrated MANET-Internet network therefore requires an efficient mobility mechanism at the MANET level, which is known as micromobility. An efficient micromobility protocol should ensure a fast and seamless handover, and should maintain ongoing session connectivity.

This paper proposes a novel and robust solution for integrating a MANET with the wider Internet [5], based on OLSR. OLSR is proactive protocol that commonly used in MANET field [8–11]. The proposed system modifies OLSR to serve the purposes of the integration. Most of the systems proposed in the literature use traditional mechanisms for gateway information dissemination and discovery, such as proactive, reactive, and hybrid gateway discovery, which operate independently from the underlay routing. However, in the proposed system, OLSR routing messages are reengineered and optimized to meet the needs of the integration, without requiring additional routing messages for gateway discovery. The proposed architecture includes the functionality of gateway information dissemination within the OLSR routing protocol and therefore solves the micromobility issue by eliminating the process of mobile node registration with a specific gateway. The proposed system does not require a MANET node to register with a gateway node, and mobile nodes can therefore freely move within the local MANET with no concerns regarding the disruption of connection with another node in the integrated network. The performance of the proposed system is evaluated using network simulator and compared to an existing system. The result of the evaluation shows the robustness of the proposed system.

The rest of the paper is organized as follows. Section 2 introduces the main challenges of integrating a MANET with other networks and gives an overview of the main works related to MANET integration. Section 3 describes the proposed system. The performance of the proposed system is demonstrated by means of simulation. The simulation settings and performance metrics are covered in Section 4, and the results of an evaluation are then presented. A performance comparison of the proposed system is also carried out in Section 5. Finally, the conclusion and a summary of this work are given in Section 6.

2. Challenges and Related Work

2.1. Challenges of Integrating a MANET with the Internet. In order to enhance the application scope of a MANET, integration with other network architectures is essential. The integration of different network architectures poses many challenges and issues, such as gateway discovery, gateway selection, load balancing, security, mobility, and load management. The main challenges for MANET-Internet integration are discussed below:

Gateway discovery: gateways play a vital part in integrating a MANET with the Internet, as they act as the interface between both architectures. MANET nodes need to discover gateways in order to forward their traffic to the Internet, meaning that in a multiple-gateway MANET, gateway discovery can increase traffic delay and overhead [12], e.g., when a MANET node uses a distant gateway where there are other gateways nearby. In general, gateway discovery mechanisms can be divided into three categories: proactive, reactive, and hybrid approaches.

In proactive discovery, a gateway node periodically broadcasts advertisement messages with all the information required to enable MANET nodes to identify the gateway. Upon receiving an advertisement message, a mobile node can set up a new route to the gateway or update existing ones. Thus, the procedure is initiated by the gateway node itself.

In contrast, in reactive discovery, the procedure is initiated by MANET nodes on demand. A MANET node requests a route to a gateway by broadcasting a route request message to the gateway nodes. In response, gateway nodes unicast a route reply to the initiator of the request. Upon receiving the reply message, the source node creates or updates the entries in its routing table for the responding gateways, selects the appropriate gateway, and then forwards messages to it [13].

The hybrid discovery mechanism combines both approaches in such a way that a proactive strategy is used to reach nodes within a local zone. Nodes that reside outside the gateway zone use the reactive gateway discovery strategy to discover and communicate with gateway nodes.

Gateway selection: more than one gateway may be discovered, and this inevitably requires a decision on the most suitable gateway. Many schemes for selecting the gateway are reported in the literature [14] and can be distinguished according to the criteria used. Some approaches focus on the criteria related to the gateway, some use criteria related to the route to the gateway, and others consider both the gateway and the route to the gateway.

(i) Gateway-based selection: in this approach, different gateway parameters are used when selecting the gateway nodes, such as signal strength, gateway mobility speed, and remaining power [15]. Gateway utilization, the length of the gateway interface queue, and the gateway with the minimum number of neighbors have also been considered when selecting a gateway

(ii) Route-based selection: with regard to the route, one easily obtained metric is the hop count between the source node and the gateway. However, this may result in a bottleneck. Other parameters related to the route include the data rate of the channel and the mobility of the nodes along the available route

(iii) Hybrid (gateway and route-based) selection: in this scheme, a combination of parameters relating to the route or the gateway are considered when selecting the appropriate gateway. For example, the hop count along the path can be used in addition to the gateway queue length

Load balancing: load balancing is one of the key challenges that require consideration. A load balancing strategy distributes MANET-Internet traffic between existing gateways, thus avoiding heavily loaded gateways where there are less loaded ones. The load balancing mechanism is applied at various points, e.g., during gateway discovery or gateway selection. Several strategies have been proposed to address the issue of load-balancing for integrated MANET-Internet networks [16], and the parameters considered include the queue length at the gateway, the number of nodes registered with the gateway, bandwidth, traffic load, and distance to the gateway.

Security: an integrated MANET-Internet architecture is susceptible to security attacks in both the Internet domain and the MANET domain, which can cause connectivity disruption. Any possible attack on a traditional MANET (such as a malicious node, a black hole attack, or lack of authentication) is also possible in the integrated architecture. Attacks on both the Internet connectivity and the MANET therefore need to be minimized when designing an integration architecture [2, 17].

Mobility: one of the characteristics of a MANET is mobility. The network topology is subject to change during the network's lifetime, and as a result, the connection between a MANET node and its corresponding entity (through gateways) in the integrated network may be disrupted. In order to resolve these issues, mobility management routing protocols are used. These protocols take responsibility for managing mobility either between different domains (macromobility) or between different subnets within the same domain (micromobility) [12, 18, 19].

2.2. Related Work.

A robust and flexible scheme for the Internet connectivity was proposed in [4], based on the design of AODV. This system modified the route request and route reply mechanism in AODV to serve the purposes of gateway discovery. A node starts the procedure of route discovery by flooding the network with route requests, in the same way as in normal AODV. Upon receiving a route request, the gateway node determines the address locality, i.e., whether the destination is an Internet address or is within the local ad hoc network. If the locality check returns an address for a host on the Internet, the gateway sends a route reply to the initiator of the route request on behalf of the destination. The route reply message is extended to carry the IP address of the internet host, and this extension is used to create a new route entry in the source node routing table pointing to the Internet host. This entry is marked with a special flag to allow a node to distinguish it from other MANET routes. The system does not support intermediate mobile node replies for gateway discovery.

The work in [20] proposed a quality of service- (QOS-) oriented distributed routing protocol, QOD, for integrated networks. This approach transforms the typical packet routing issue into a dynamic resource scheduling issue. A QOD source node sends its traffic directly to the access point if it is within range of the access point; otherwise, the source node selects one of its neighbors that can provide QOS to deliver its traffic to the base station. The base station consequently forwards the traffic to the destination. The system schedules and selects one of the neighbors based on their channel condition, queuing condition, and mobility, with the main goal of reducing transmission time and increasing network capacity.

In [21], a time-stamp-based proxy adaptive gateway discovery algorithm was proposed that adopts a hybrid gateway discovery approach, i.e., using both reactive and proactive gateway discovery schemes. The proposed system does not flood the whole network with gateway advertisements; instead, it divides the network into reactive and proactive zones. A node on the border of the proactive zone acts as a proxy node and replies to the originator from the neighbor with a gateway reply. The route reply from the proxy node is unicast in order to reduce the overhead. The time-stamp-based proxy adaptive gateway discovery algorithm introduces an additional metric called the time-stamp factor in the gateway advertisement message. The time stamp is used by the mobile node to choose a gateway with a high response time.

The authors of [22] proposed a system that adopted the mechanism of maximal source coverage for adaptive gateway discovery proposed in [23]. The main goal of maximal source coverage is to control the size of the proactive zone. In this approach, the scope of the gateway is dynamically adjusted to control the traffic in the MANET, where the size of the proactive advertisement zone increases as needed. Moreover, this study combined maximal source coverage with an algorithm for load balancing [24].

In [25], a system was proposed based on the AODV protocol. A proactive gateway discovery scheme was used in which gateway nodes periodically broadcast gateway advertisement messages. The system does not allow a normal MANET node to register directly with a gateway node and instead introduces a special gateway selector node to the structure of the integrated network. Registration with the gateway is therefore limited to the gateway selector nodes only. Fixed gateways support communication with both the Internet and with the MANET, and the routing in the system is modified to work based on the priority of the traffic. Each node in this scheme uses two types of queue to distinguish traffic priority, and gateways are divided into two types based on the traffic. The gateway selector node can then redirect traffic to the appropriate gateway based on its type.

The studies in [26, 27] proposed a system that uses a proactive gateway discovery scheme. The location of a gateway is periodically advertised locally by broadcasting gateway advertisement messages. However, these advertisements are only broadcast to the nearest nodes within the coverage area of the gateway node. A gateway node also uses a notification mechanism to notify MANET nodes of its heavy load. This notification is then used by the MANET nodes to redirect external traffic to other gateways in the network. The notification scheme is implemented by monitoring the queue size, where each gateway monitors its queue size and a heavy load notification is triggered when the size increases above an average number.

The work in [28] proposed iAODV-RO as a modification for an interconnected protocol Internet ad hoc on-demand distance vector (iAODV) [29] to provide the MANET-Internet connectivity with route optimization. The iAODV has a wired network interface and supports integration with the Internet. In this structure, there are interconnected nodes (ICNs) that are equipped with multiple interfaces and act as gateways between a MANET and a wired network: WDN, which has a wired interface only, and WLN, which has a wireless interface. This iAODV-RO scheme was implemented on embedded devices.

A contention-aware adaptive-based routing protocol was proposed in [30]. This system modified OLSR and AODV to improve the process of choosing an optimal path for routing from MANET to the Internet, based on the awareness of the congestion that may occur at the link layer along any route to a gateway. A mobile node resolves contention based on Request To Send frames, Clear To Send frames, data frames, and acknowledgements. The contention information at the link layer is then incorporated with the network layers (OLSR and AODV) through crosslayering to enhance their awareness of the congested paths, thus allowing MANET nodes to choose the least congested route.

The study in [31] proposed a QOS-based load balancing mechanism for a MANET-Internet integrated network to improve data delivery within the integrated network. The proposed system uses a reactive gateway discovery scheme, and mobile nodes run the AODV as the routing protocol. In order to connect to the Internet, a mobile node must find a gateway by broadcasting a gateway solicitation message, and in response, each gateway replies with a gateway advertisement message. The gateway advertisement message is modified to carry QOS-related information that includes the length of the interface queue, the routing table entry, the connection degree, and the hop count. This information can be then used by mobile nodes to determine the optimum gateway.

Other researchers have proposed an adaptive gateway discovery scheme for integrated networks based on the AODV routing protocol [32]. This system adopts an on-demand gateway broadcast strategy, the aim of which is to meet only the actual needs of the mobile nodes for gateway advertisement messages. This system ensures that gateways broadcast advertisements according to the requirements of MANET nodes: if there is no demand, the gateway will not broadcast an advertisement message. Participating mobile nodes monitor the route to the gateway, and whenever a source node predicts a link disconnection, it notifies the corresponding gateways in unicast manner. Upon receiving a notification, the gateway immediately broadcasts gateway advertisements. Each node receiving the message will also update its routing entries.

The study in [33] extended the maximum source coverage algorithm for a MANET integrated network. Based on maximal source coverage, a gateway sends the next gateway advertisement with a TTL equal to the hop count for the furthest active node in the proactive zone. However, the proposed system modifies the maximal source coverage algorithm by introducing new parameters to control the size of the coverage area. The expansion of the coverage area is determined based on the number of active sources outside the proactive coverage area and the number of active users within the proactive zone. If the number of active sources from outside the coverage area reaches a certain threshold, a gateway node expands the proactive zone to cover these active sources. The parameters are used to determine to how far the gateway advertisements should travel.

An integrated infrastructure and infrastructure-less network based on QOS DSDV was proposed in [34]. In this structure, there is a gateway node that acts as a foreign agent and a mobile IP proxy for other mobile nodes. The gateway is placed near to an access point which connects it to the external network. The gateway node does not broadcast advertisement messages for the purposes of registration, and a MANET node therefore has to send registration information to the gateway, which in turn sends the registration to the initiator's home agent. After successful registration, the MANET node will be notified via its gateway node. The purpose of the gateway is to maintain the registration information of all the ad hoc nodes which required access to the external network.

The study in [35] proposed an integrated network that used AODV as the MANET routing protocol. The process of discovering a gateway to the Internet is initiated by the mobile node itself. The node is required to broadcast a gateway discovery message with limited TTL, and upon receiving the gateway discovery message, the gateway node must reply by broadcasting a gateway advertisement message. This message is sent with a TTL equal to the TTL of the received gateway discovery message, meaning that broadcasting gateway advertisements are dependent on receiving a gateway discovery message. The goal is to avoid periodically flooding the network with gateway advertisements. This system therefore uses a reactive gateway discovery scheme where MANET nodes discovers the gateway. It also uses a proactive gateway discovery scheme where the gateway node broadcasts gateway advertisements.

As can be seen from the above discussion, the reactive, proactive, and hybrid gateway discovery schemes are used by most of the proposed integrations in the literature to serve the purpose of gateway discovery. Traditional discovery mechanisms incur the costs of the additional tasks in the routing protocols. The proposed system therefore avoids using a traditional gateway discovery procedure and instead optimizes the existing OLSR MANET routing protocol to disseminate gateway information.

3. Proposed System

The system proposed here aims to integrate an isolated MANET with the wider Internet network. The proposed system is based on an OLSR MANET routing protocol, but modifies OLSR to serve the purposes of integration. The majority of the proposed systems in the literature use traditional mechanisms for gateway information dissemination and discovery, such as proactive, reactive, and hybrid mechanisms that operate independently from the underlay routing. However, in the proposed system, OLSR routing messages are reengineered and optimized to meet the needs of the integration without requiring additional routing messages for gateway discovery. The proposed architecture includes the functionality of gateway information dissemination within the OLSR routing protocol.

Figure 1 shows the overall architecture of the integration considered in this paper. In the proposed architecture, a mobile node acts as a gateway forwarding MANET traffic to the Internet and vice versa. A node can be a gateway if it is equipped with two network interfaces and is within radio range of the access point. The first interface connects with the access point, and the second communicates with normal MANET nodes.

There are two cases in which MANET nodes can obtain connectivity to the external Internet. In the first, the MANET node resides within the coverage area of the gateway; the node communicates directly with the gateway, which in turn forwards the traffic to the internet. In the second case, the MANET nodes are located outside the radio range of the gateway and can access the gateway via other MANET nodes which relay their traffic to the gateway, requiring more than one hop.

The following subsections describe in detail a process by which a gateway can advertise itself throughout the network without involving new routing messages and explains the new routing mechanisms that is introduced to the OLSR protocol to smooth the integration, and how this new information is processed and how the routing table entries are consequently calculated.

3.1. Dissemination of Gateway Information. The proposed structure aims to build an integrated MANET-Internet network using a new technique for gateway discovery that disseminates the gateway location at minimum cost. The proposed system therefore optimizes the existing OLSR MANET routing messages to distribute information about Internet gateways.

OLSR is a proactive MANET routing protocol that builds routes to all other nodes in the network in advance of their use. For the purpose of maintaining up-to-date routing entries, each mobile node periodically broadcasts hello message with TTL equal to 1. These hello messages are used to discover the local topology and detect physical neighbors. Hello messages are omitted with a TTL of one, meaning that they will not travel outside the initiator radio range. These hello messages will therefore not suffice for the dissemination of gateway information. In the proposed system, the OLSR hello message is optimized by network gateways to advertise themselves to their physical neighbors. Hence, a gateway node advertises itself as a gateway by changing its hello message to include information stating that it works as a gateway to the Internet.

The format of the OLSR hello message contains a reserved field of two bytes, which can be used for future extension, as stated by the author of the protocol. The proposed system utilizes the first byte of the field in the hello message format to advertise the status of a node being a gateway to the Internet.

$$\begin{aligned} \text{Not\_Gateway} &= 0. \\ \text{Gateway} &= 1. \end{aligned} \tag{1}$$

The gateway field of a node may be set to one of the integer values, 0 or 1. A mobile node that acts as a gateway may therefore set this field to one, while MANET nodes that are not working as gateways may set the field value to zero. The rest of the possible integer values and the left byte can be used for any further extension of the proposed system. The gateway field will take on a value whenever a MANET node creates a hello message. As a consequence, information on a node being a gateway to the internet can be spread to the one-hop physical neighbors through the modified OLSR hello message whenever a hello message is sent. Figure 2 shows the format of the modified OLSR hello message.

3.2. Maintaining Gateway Information at Physical Neighbors. The hello message is intended to serve three main purposes in OLSR: link sensing, neighbor detection, and MPR selection. When conducting link sensing, OLSR stores the information in what is known as the local link information base, which consists of set of link tuples. For the neighbor detection, OLSR maintains a base called the neighborhood information base, which consists of a neighbor set and a two-hop neighbor set. For the MPR selection, it stores information about the selected MPR in the so-called MPR set and information about nodes that have chosen the current node as their MPR in the MPR selector set. To distribute information about the gateway in the proposed system, the structure of the local link information base and the neighbor set are optimized to hold information regarding gateways, as described below.

Local information base: when a node receives a hello message, it processes the message to populate the local link information base. More precisely, the node holds a link tuple for each individual originator of hello messages, in order to store information about all possible links. In the proposed system, the link tuple format is changed, and a new field called Is_Gateway is added to the structure of the link tuple. The value of Is_Gateway is set according to the value of the

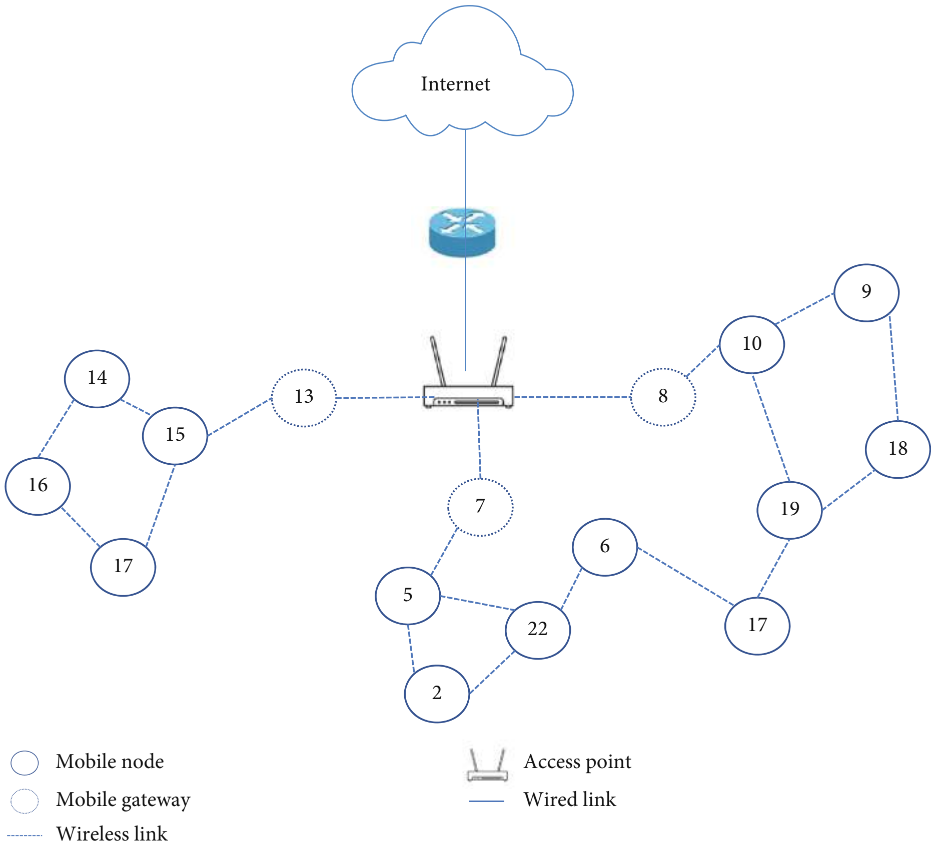

Figure 1: The structure of the proposed integration scheme.

<table>
<tr><td>Reserved</td><td>Gateway</td><td>Htime</td><td>Willingness</td></tr>
<tr><td>Link code</td><td>Reserved</td><td colspan="2">Link message size</td></tr>
<tr><td colspan="4">Neighbor interface address</td></tr>
<tr><td colspan="4">Neighbor interface address</td></tr>
<tr><td colspan="4">..</td></tr>
<tr><td>Link code</td><td>Reserved</td><td colspan="2">Link message size</td></tr>
<tr><td colspan="4">Neighbor interface address</td></tr>
<tr><td colspan="4">Neighbor interface address</td></tr>
</table>

Figure 2: Modified format of the OLSR hello message.

gateway field in the received hello message.

$$\text{Is\_Gateway} = \text{value of the gateway field in an arriving hello message.} \quad (2)$$

The modified record structure of a link tuple in the proposed solution therefore consists of local interface address, the interface address of the neighbor node, the link symmetric time, the time of hearing neighbor interface, the record expiry time, and the Is_Gateway field.

By this time, the physical neighbors of a gateway node are aware of the existence of the gateway. However, information about the gateway needs to be disseminated further to nodes that are not physical neighbors of the gateway node. In order to facilitate this dissemination mechanism, each physical neighbor is required to store gateway information in another set called the neighbor set, which will be used later when disseminating gateway information to the entire network using another routing messages of OLSR. More details of this process are given in the next subsection.

Neighbor set: the neighbor set consists of a neighbor tuple for each physical neighbor and records information related to that neighbor. The structure of the neighbor set is also modified to include the status of the neighbor as a gateway node. The new structure of the neighbor tuple consists of the main address of the neighbor, its status as an symmetric or asymmetric node, the willingness of the node to carry traffic on behalf of others and finally, the new field storing its status as a gateway node. A neighbor tuple is updated whenever the receiving node receives and processes a hello message containing information about the corresponding neighbor.

3.3. Dissemination of Gateway Information beyond Physical Neighbors. As hello messages are created with a TTL of one and are never forwarded beyond physical neighbors, the information about these gateways is consequently distributed only within the radio range of the gateways themselves. A new mechanism is therefore required to publicize the gateways throughout the MANET network. This can be achieved by using special message in OLSR called the topology control (TC) message.

OLSR uses TC messages for the purpose of diffusing routing information to the whole network. However, OLSR uses an optimized broadcasting mechanism to avoid flooding the network. In the broadcasting mechanism used, only nodes that have been selected as MPR by their neighbor are allowed to rebroadcast received messages that are intended to be diffused in the network. TC messages are broadcast with TTL equal to 255 and are only retransmitted by other MPR nodes. Based on OLSR, nodes select its MPR from its one hop neighbors providing that it can reach all the 2 hop neighbors through selected MPRs.

The proposed system therefore uses TC messages to disseminate gateway information to the entire network. Since TC messages are generated by MPR nodes, the propagation of gateway information using TC message follows the following pattern.

Since each OLSR node selects one or more of its neighbors to act as its MPR, the gateway itself must select one or more of its neighbors as its MPR. As Figure 3 shows, the gateway node 13 will select only node 15 as its MPR, since it can reach most of the two-hop neighbors through this node. Moreover, MPR node 15 is a physical neighbor of the gateway and hence is expected to receive hello messages from the gateway. Node 15 is therefore aware of the existence of the gateway and can attach gateway information to the TC messages it generates.

The proposed system piggybacks the TC message with information related to internet gateways. The information can be retrieved using the modified neighbor set, which is populated upon receiving the hello message as illustrated in the previous section. The process of generating the TC message is changed, so that the generator of TC message examines the neighbor set to identify the addresses of any nodes that are gateways to the internet. It then prepares a list of these addresses, called a gateway list, which is then attached to the TC message to allow gateway information to be diffused further in the network. Figure 4 shows the overall structure of the TC message with the gateway list attached to it. The procedure of attaching gateway list to a TC message is carried out only by those nodes which have been selected by gateways as their MPR nodes. Moreover, the list will not be more than few bytes that are the IP addresses of neighboring gateways.

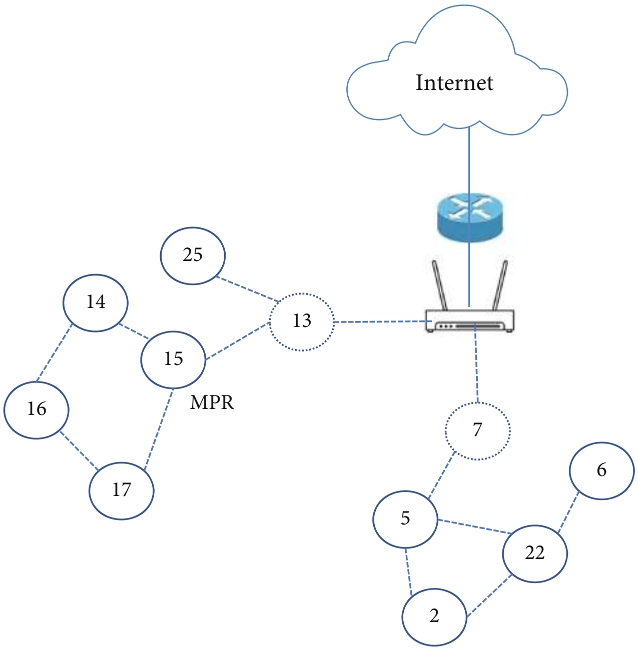

Figure 3: Propagation of gateway information via TC messages.

Ansn	Reserved
Advertised neighbor main address	
...	
Advertised neighbor main address	
Gateway main address	
...	
Gateway main address	

Figure 4: TC message with attached gateway list.

Another information base which is maintained by each OLSR node and optimized in the proposed system is the topology set, which consists of topology tuples. OLSR maintains at least one topology tuple for each destination in the network. A topology tuple records the main address of a node, the address of the one-hop neighbor of the main address in the current record, and the sequence number and expiry time of this record. It is populated through TC messages. When a node receives a TC message, it updates each existing record in the Advertised Neighbor Main Address from the arriving TC message. If there is no existing record that matches the Advertised Neighbor Main Address, it creates new one. The topology tuples are then used to calculate the routing table.

The proposed system modifies the structure of the topology tuples to include a new field that stores the gateway status of the main address field in the current tuple. The new contents of a topology tuple will therefore be the main address of a node, the one-hop neighbors of the main address, the sequence number, expiry time and gateway status.

3.4. Gateway List Processing. When a node receives a TC message, it must maintain a topology tuple for each advertised address in the TC message. The processing node creates a new tuple for the advertised neighbor main address if no such tuple has been created. However, the processing node only updates the corresponding expiry time if the tuple for the advertised neighbor main address already exists. After processing the TC message according to the OLSR standard, a node moves a step forward in processing the piggybacked list which has been introduced by the proposed system. This list points to any neighboring node of the originator of the TC message that acts as a gateway to the external network. By this time, the receiving node has already created or updated the corresponding topology tuples for each address in the piggybacked list, since the attached gateway addresses in the piggybacked list are neighbors of the originator of the arriving TC message and are therefore already included in the arriving TC message as the advertised neighbor main address. The piggybacked list is then used only to update the new proposed field in the topology tuple that indicates whether the main address of this record is a gateway to the internet. The gateway status in each topology tuple will therefore be updated to zero or one if and only if the main address of the topology tuple exists in the piggybacked list.

OLSR uses TC messages to diffuse the network topology throughout the network. Thus, each node in the network will receive a TC message from one or more neighbors of the gateways that hold a piggybacked list of the gateway nodes in the network. As a consequence of processing the TC messages, each mobile node will have a topology tuple in their topology set that points to a gateway to the external network. The topology set will then be used to calculate the routing table. Therefore, the use of TC messages guarantees the propagation of gateway node addresses throughout the network for no extra cost.

3.5. Calculation of the Routing Table. The OLSR routing table is built at each node based on its information base and the topology set. The hello and TC messages are the main sources for populating the information base and the topology set. Any changes that are detected in any of these sets (the link set, the neighbor set, the two-hop neighbor set, the topology set, and the multiple interface association information base) trigger the process of recalculating the routing table to update the routing entries. Each OLSR node creates a routing entry in the routing table for each possible destination, in the following format:

$$\begin{gathered} 1-\mathrm{R\_dest\_addr} \quad \mathrm{R\_next\_addr} \quad \mathrm{R\_dist\_addr} \quad \mathrm{R\_iface\_addr}. \\ 2-\cdots\cdots \\ 3-\cdots\cdots, \end{gathered} \tag{3}$$

where R_dest_addr is the destination that is R_dist_addr hops away from the current node, and R_next_addr is the next hop in the route to the destination node. The next-hop node can be accessed using the local interface R_iface_addr.

In the proposed system, the routing table format for a routing entry is changed so that it reflects the nodes' awareness of existing mobile gateways in the network, thus helping each MANET node to identify gateways to the external network. A new field named G_to_int is introduced in the routing entry format to indicate whether the current destination address of the routing table entry is a gateway to the Internet. The new format of the routing table is as follows:

$$\begin{gathered} 1-\mathrm{R\_dest\_addr} \quad \mathrm{R\_next\_addr} \quad \mathrm{R\_dist\_addr} \quad \mathrm{R\_iface\_addr} \quad \mathrm{G\_to\_int}. \\ 2-\cdots\cdots \end{gathered} \tag{4}$$

The new field takes a value of one if the R_dest_addr in the current routing entry is one of the gateways to the external network, while if the destination is just a normal MANET node, the value of G_to_int is set to zero. The information about the status of R_dest_addr as a gateway can be retrieved from the topology set during the calculation of the routing table, since the topology tuple has been modified to store the gateway status of the main address in a topology tuple.

The main goal of the OLSR as a proactive routing protocol is to build a routing table in advance that enables each individual node to route traffic to any node in the network. The proposed version of OLSR therefore builds routing entries in advance that include additional information about the destination of the entry, declaring whether or not this destination is a gateway to an integrated network. Whenever a MANET node wants to exchange traffic with an external host in the integrated network, i.e., a host on the Internet to which it does not have a route, our system routes this traffic towards a MANET node whose route entry value of G_to_int is one with the minimum hop count.

Overall, our modification of the OLSR protocol to facilitate proper integration of MANET with an external network can be summarized in the following steps:

Step 1. modify the hello message to carry gateway information, in order to propagate the existence of the gateway to the one-hop physical neighbors.

Step 2. change the structure of the link tuple and neighbor tuple to enable them to store gateway information.

Step 3. upon receiving a hello message, the receiver updates the value of the gateway field in the corresponding link tuple and the corresponding neighbor tuple.

Step 4. optimize the TC message to disseminate gateway information beyond the physical neighbors. This is done by piggybacking a TC message with the list of gateway nodes of which the sender of the TC is aware.

Step 5. change the topology tuple structure to include a new field that stores the gateway status for the current tuple.

Step 6. extend the processing of the received TC message to include the piggybacked list. The list is used to update the gateway status in the corresponding topology tuples.

Step 7. introduce a new field in the routing table entry format to indicate whether or not the destination of the current route entry is a gateway.

Step 8. if a node wants to connect to the external network, messages are forwarded towards a MANET node that acts as a gateway using the modified routing table.

4. Evaluation of the Proposed System

4.1. Simulation Parameters and Performance Metrics. Extensive simulations were conducted to evaluate the performance of the proposed system using the OMNET++ [36] network simulation platform. Although OMNET++ is not a network simulator itself, for each domain specific functionality, it provides model frameworks that are developed as independent projects. The INET [37] framework is one of the projects used in this research to simulate the MANET. The INET model is considered the standard model library for OMNET++, as it supports the Internet stack and many other Internet protocols and contains models for wired, wireless, and mobile networks and MANETs.

Table 1 shows the simulation parameters for the scenario in which the proposed system was evaluated. Mobile nodes move randomly according to the random waypoint mobility model. Nodes randomly choose a destination and move toward it with a speed up to the maximum. Speeds of 1, 2, 3, 4, and 5 m/s were used in the simulated scenario. Once a node arrives at a previously chosen destination, it pauses for a period known as the mobility model wait time, which is set to zero here. The propagation model is set to a two-ray ground reflection model, which also considers the ground reflection path. At the MAC layer, the IEEE 802.11 g protocol was used, and its parameters were set to the default values. A constant bit rate was used for the simulated traffic, and each MANET node sent about 10 packets per second, with a packet length of 512 bytes to a destination outside MANET network.

Table 1: Simulation configuration.

Parameter	Value
Simulator	OMNeT++
Network size	1000 m x 1000 m
Propagation model	Two-ray ground reflection
Number of nodes	30, 40, 50, 60, 60, 70, 80, 90, and 100
Mobility model	Random way point
Node speed	1, 2, 3, 4, and 5 m/s
Measurement time	900 s
Transmission range	250 m
Number of sources	All nodes
Network stabilization	Between 20 and 30 s
Simulation repetitions	5
MAC layer	IEEE 802.11
Number of packets sent	10 packets/s
Packet length	512 bytes
Mobility model wait time	0
Number of gateways	2

The performance metrics that are applied in this research to evaluate the proposed system are commonly used for evaluating ad hoc routing protocols and are as follows:

(i) Success ratio: this is the ratio between the number of data packets sent by the constant bit rate application via MANET nodes and the number of data packets successfully received by an Internet host in the integrated network over the measurement period

(ii) Average end-to-end data delay: this is the average time required by a data packet in the proposed system to reach the final destination in the integrated network. The end-to-end data delay includes buffering for routing discovery latency when the route is not available, delays at the interface queues, retransmission delays, processing, and queuing of the messages at the originator and intermediate nodes

(iii) Routing packet overhead: this is the total number of packets released over the network by all MANET nodes over the simulation period. For a packet that travels over many hops, each transmission between adjacent nodes is counted as one transmission

4.2. Simulation Results. Figures 5 and 6 show the success ratio for the proposed system when evaluated in the aforementioned scenarios. Figure 5 shows the packet delivery ratio as a function of network size (70, 80, 90, and 100 nodes) and mobility speed (2, 3, 4, and 5 m/s). As the graph shows, the node mobility has significant effect on the success ratio of the proposed system. At a lower speed (2 m/s) of the node mobility, the proposed system performs well, delivering more than 97% of the generated data to nodes in the integrated network. Good performance is even achieved in the largest

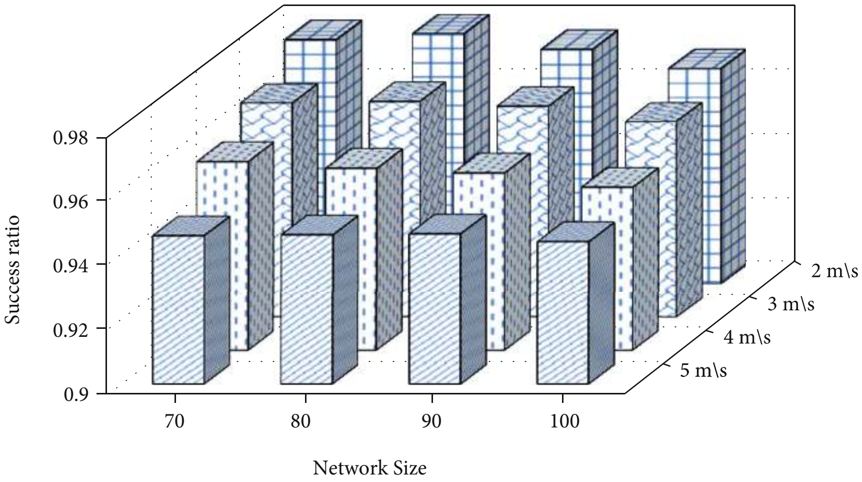

Figure 5: Success ratio.

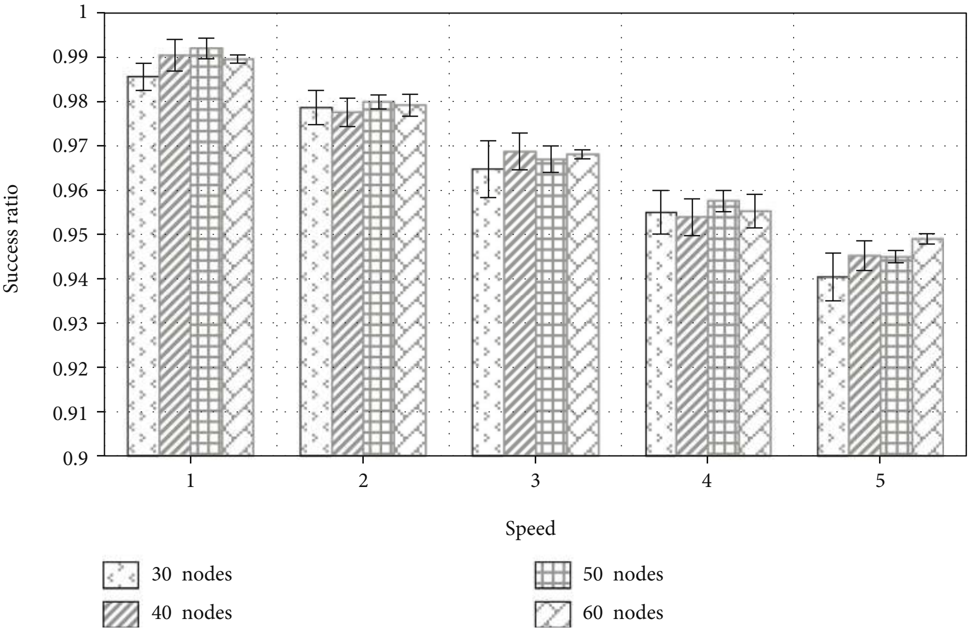

Figure 6: Success ratio.

evaluated network of 100 mobile nodes. However, as the movement speed of the nodes increases up to 5 m/s, the success ratio of data delivery to the external network decreases. Route breaking as a result of fast movement is likely to be the main reason for this decrease.

Figure 6 illustrates the success ratio for data delivery in the proposed system when evaluated in scenarios with a small number of mobile nodes (30 to 60 nodes), as a function of movement speed. Similarly to Figure 5, the figure depicts the effects of movement speed on the performance of the system, where the delivery ratio decreases as the network size and movement speed increase. However, the system is still able to achieve a success rate of more than 94%, even at the highest simulated speed.

Figure 7 illustrates the average end-to-end delay experienced by each data packet in reaching the host in the external network. It shows the results for network sizes of 30 to 100 mobile nodes, at different movement speeds. As the figure shows, the end-to-end delay increases as the number of participating nodes increases. The obvious reason for this increase in the average delay is that with more nodes in the network, more data need to be delivered to the external host in the integrated network via the gateways; hence, queuing at the gateways and possible collisions when routing to the gateway are the main causes of this high end-to-end delay.

The average delay is almost the same for networks consisting of 70 nodes or less, for movement speeds of 1, 3, and 5 m/s. However, a discrepancy can be seen in the results at

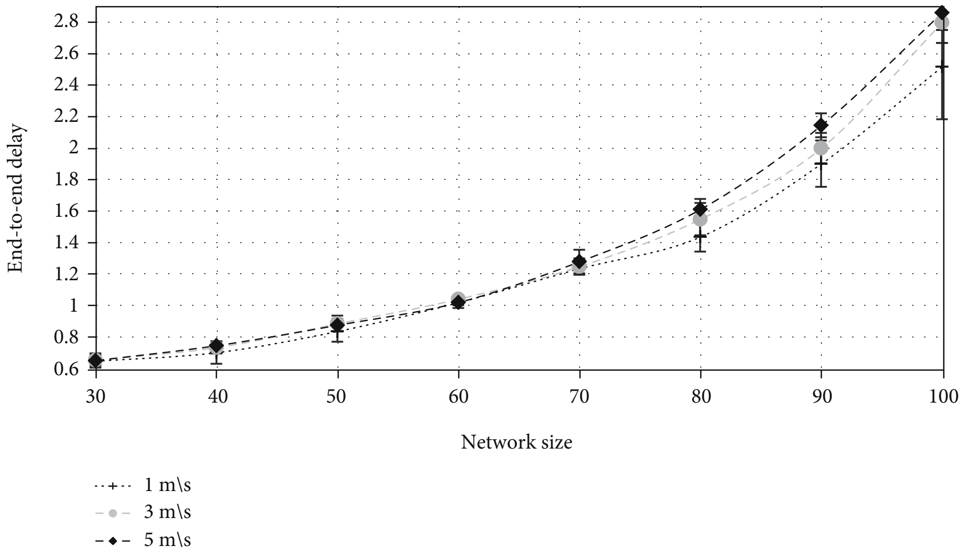

Figure 7: End-to-end delay.

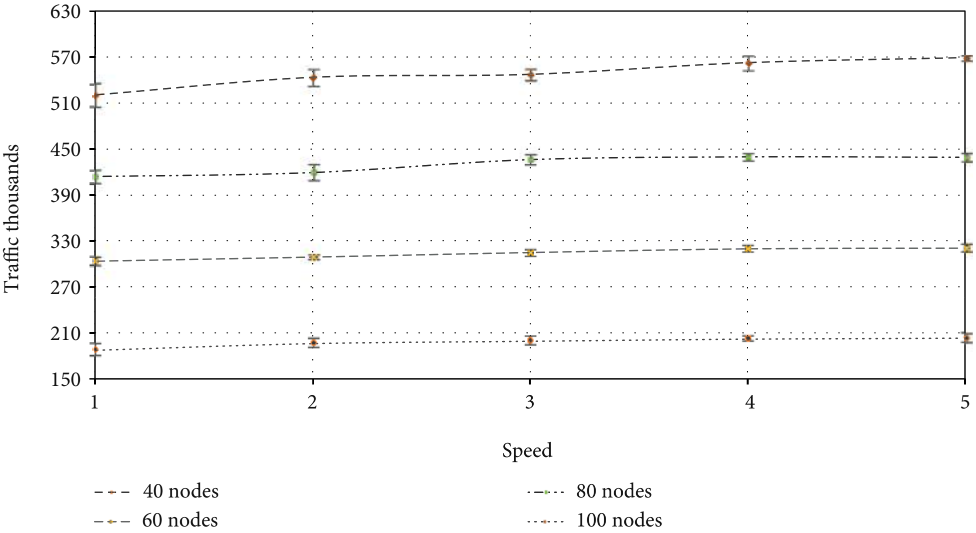

Figure 8: Traffic.

different speeds for network sizes of 80 and higher. This is explained by the fact that at higher mobility speeds and in larger networks, there will be frequent changes in the network topology, resulting in route updates and hence higher delays for data to reach the final destination.

Figure 8 shows the overall number of packets released over the simulation period for networks of 40, 60, 80, and 100 nodes versus movement speed. The total traffic released in all of the networks is affected by the movement speed, as can be seen from the figure. However, the increase is significant for mobile networks of 100 nodes, where more than 60,000 packets were released at a speed of 5 m/s compared to the same network size with slow mobility.

In order to see the effect of sending a high rate of data traffic to the external host in the integrated networks, the proposed system was evaluated with varying numbers of packets sent per second in a network with 80 nodes. The number of packets sent to the host in the integrated network was set to 5, 10, 15, 17, 19 and 20 packets per second by each participating node. Figures 9–12 show the effects of sending intensive traffic on the success ratio, end-to-end delay and total traffic, respectively.

Figure 9 depicts the packet delivery ratio of the system when sending different numbers of packets via each node with low mobility speed of 1 m/s, a medium mobility speed of 3 m\s and a high mobility speed of 5 m/s. The system yields its poorest performance when evaluated at high movement speed and the best at low speed.

The performance of the system decreases gradually as the number of packets sent increases. However, the capability of

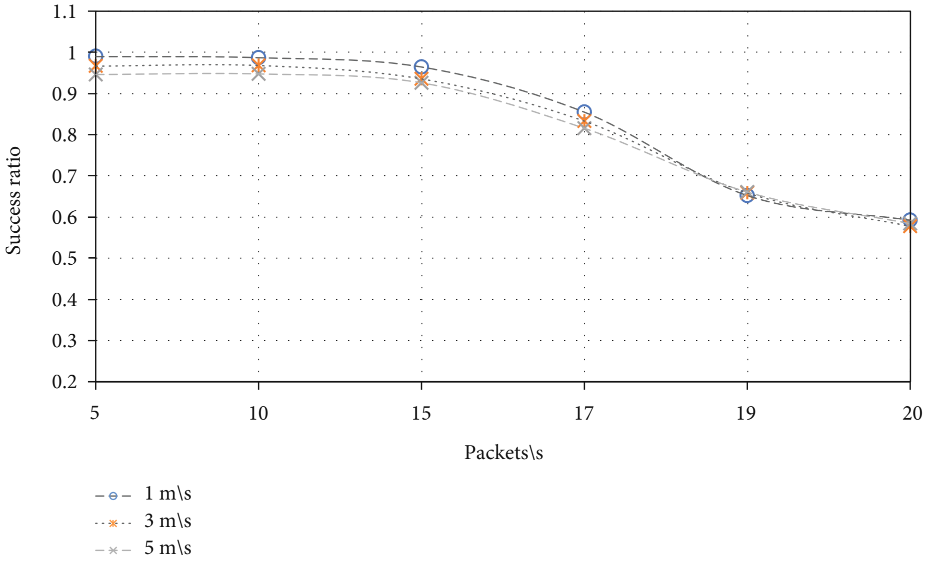

Figure 9: Success ratio in intensive scenario.

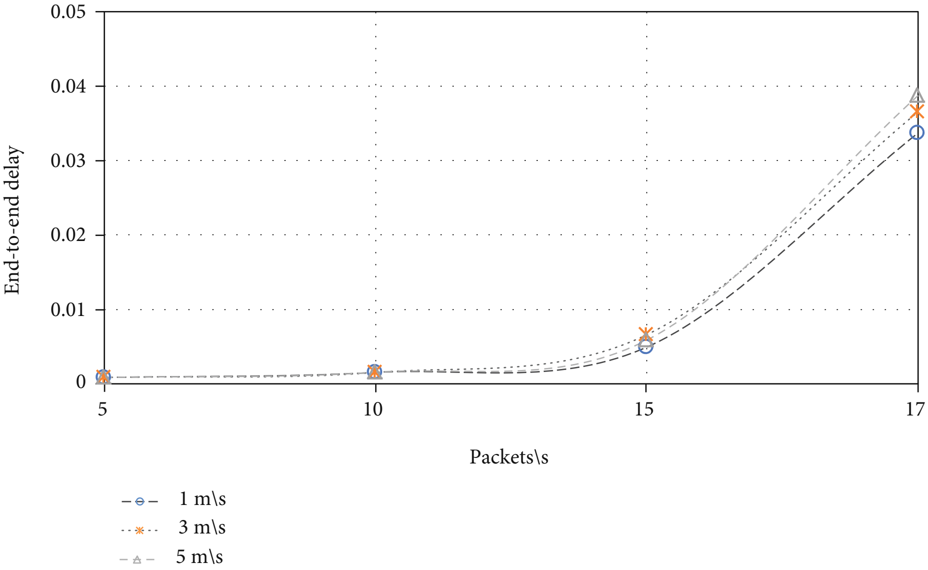

Figure 10: End-to-end delay in intensive scenario.

the system to deliver data to the external network via the gateways is drastically degraded when each node sends more than 15 packets per second. It reaches about 60% at 20 packets/s for all mobility speeds. This is likely to be the result of the collisions that occur when large amounts of data need to pass through a gateway to the other network, raising the issue of the gateway acting as a bottleneck.

The average end-to-end delay for the same network settings is shown in Figures 10 and 11. Similarly to the trend in the success ratio, the end-to-end delay increases sharply as the number of packets sent exceeds 15. This is due to the fact that a packet experiences long delays as it travels toward its final destination in the external network as result of queuing delays, especially around the gateway nodes. Moreover, collisions play a vital part in the results for the end-to-end delay, as the retransmission of colliding packets incurs additional delays compared to a situation where packets are transmitted the first time with no collisions.

The effects of heavy data traffic on the performance of the system in terms of the total traffic released is plotted in Figure 12 for a network of 80 nodes. The total traffic is expected to increase, since more data are sent as the packet rate increases. However, the network was only capable of intensive usage up to 15 packet/s scenarios where it maintains a good performance (more than 90% success rate), as illustrated in Figure 9.

The total traffic continues rising as the rate of sending by participating nodes increases, but poor performance is seen

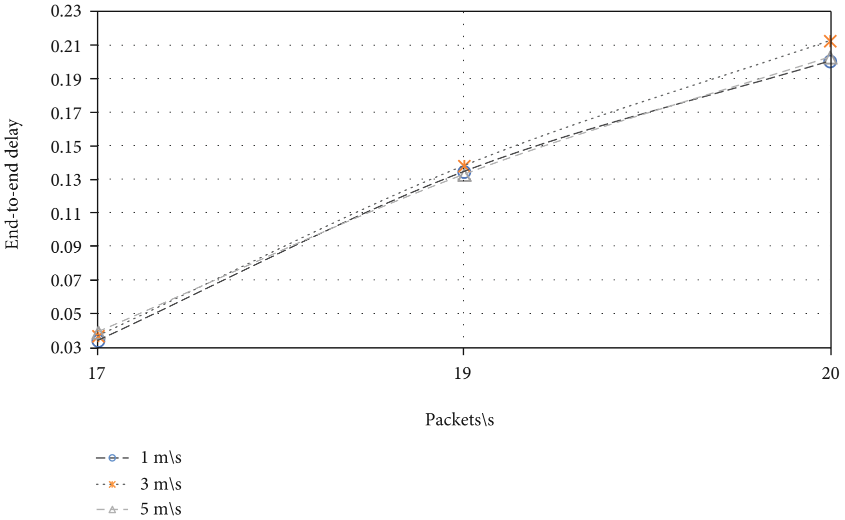

Figure 11: End-to-end delay in intensive scenario.

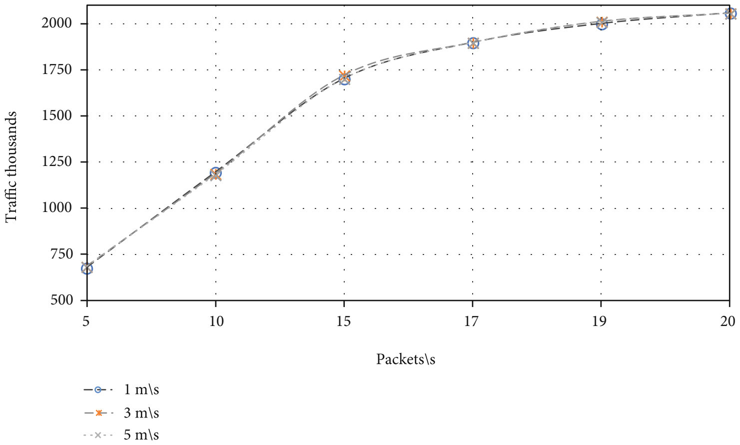

Figure 12: Traffic in intensive scenario.

as less data can successfully arrive at the integrated network. The additional traffic is mainly caused by the traffic released from the application to the external host; it is not only due to the routing load, since the interval between the routing updates implemented by the routing protocol does not change. The reason for the poor performance is likely to be due to the gateways acting as bottlenecks, especially when there is high demand to forward data to the neighboring network.

5. Performance Comparison of the Proposed System

The performance of the proposed system was evaluated and compared to the protocol proposed in [25]. The environment was set to 800 m in length and 500 m in width. The number of mobile nodes was set to 15, and two nodes acted as gateways to the external network. Six of the mobile nodes were used as traffic sources and started sending traffic after the first 5 s of the simulation. Mobile nodes moved randomly based on the random way point mobility model with 10 s as the pause

Table 2: Simulation parameters.

Parameter	Value
Simulator	OMNeT++
Network size	800 × 500 m
Number of nodes	15
Mobility model	Random way point
Node speed	1, 2, 3, 4, and 5 m/s
Measurement time	120 s
Transmission range	250 m
Network stabilization	5 s
Simulation repetitions	10
MAC layer	IEEE 802.11
Traffic type	CBR
Packet size	512 bytes
Mobility model pause time	10
Number of gateways	2
Number of sources	6

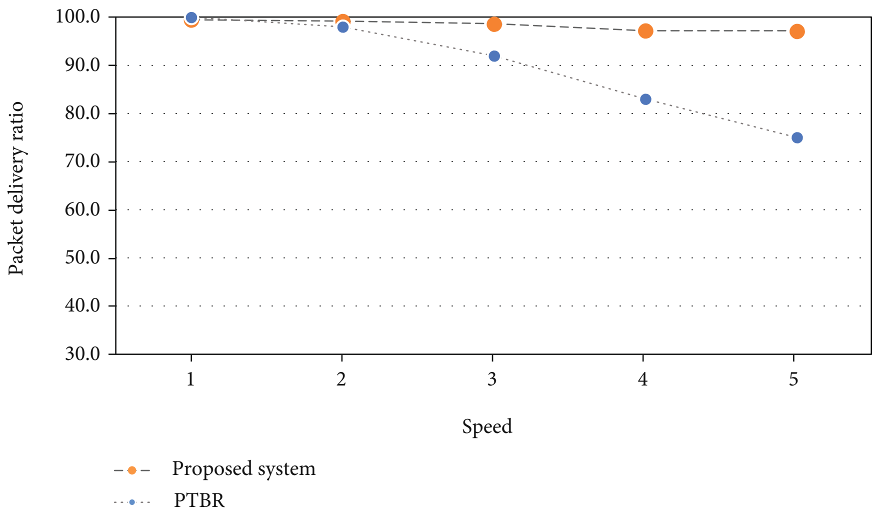

Figure 13: Packet delivery ratio.

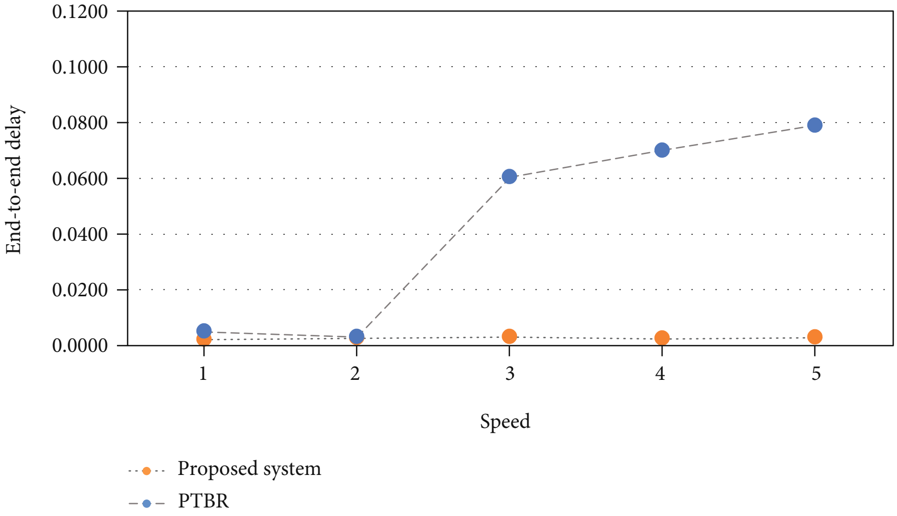

Figure 14: End-to-end delay.

time and at different speeds ranging from 1 to 5 m/s. Table 2 summarizes the simulation parameters.

Each simulated scenario was run 10 times, and the plotted result constitutes the average of these runs. Figures 13 and 14 depict the packet delivery ratio and the end-to-end delay, respectively, for both systems.

As Figure 13 shows, both systems give a good result in terms of the packet delivery ratio when the speed of mobile nodes is 2 m/s or lower. However, as the speed increases, the performance of PTBR decreases to less than 80%. The proposed system maintains better performance than PTBR for all the speeds considered and achieves a success rate of more than 95% in all the scenarios.

The average end-to-end delay incurred by a packet arriving at the external network is shown in Figure 14. At slower speeds of movement of 2 m/s or less, PTBR required a similar time to the proposed system; however, as the previous graph shows, the success rate decreased for PTBR as the mobility speed increased. The reduction in the success rate is reflected in the end-to-end performance, where the delay increases more than fivefold as the speed increases to 3 m/s from 1 m/s meaning that the system is still able to deliver traffic but with more efforts and hence, higher delay. The proposed system outperforms PTBR, as it requires less time in all of the different scenarios.

6. Conclusion

This paper proposes a novel solution for integrating a MANET with the Internet, based on the OLSR routing protocol. The proposed system optimizes existing underlay routing traffic to disseminate gateway information. It modifies number of OLSR routing messages and enhances their format to support the functionality of integrated networks within the underlay routing protocol. The hello message, topology control message, link set, neighbor set, and topology set are reengineered in the proposed system, and the routing table calculation is also modified to reflect the awareness of each node of the existing gateways in the network.

The performance of the system was comprehensively evaluated and analyzed using the OMNET++ network simulator, and the results demonstrate the capability of the system to deliver data to the external networks efficiently. The performance of the system was also evaluated and compared to an existing solution for MANET-Internet integration called PTBR. The proposed system outperforms PTBR in terms of packet delivery ratio and end-to-end delay and shows solid performance for different mobility speeds.

Data Availability

OMNET++ network simulator at https://omnetpp.org/, Inet Framework at https://inet.omnetpp.org/.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

Acknowledgments

The author would like to thank the Deanship of Scientific Research at Umm Al-Qura University, Saudi Arabia (project ID: 17-COM-1-02-0001) for the financial support.

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