Mobility Management in Wireless Mesh Networks Utilizing Location Routing and Pointer Forwarding

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***Abstract*—We propose and analyze LMMesh: a routing-based location management scheme with pointer forwarding for wireless mesh networks. LMMesh integrates routing-based location update (location routing) and pointer forwarding by exploiting the advantages of both methods, while avoiding their drawbacks. It considers the effect of the integration on the overall network cost incurred by location management and packet delivery. By exploring the tradeoff between the service cost for packet delivery and the signaling cost for location management, LMMesh identifies the optimal protocol setting that minimizes the overall network cost on a per-user basis for each individual mesh client, when given a set of parameter values characterizing the specific mobility and service characteristics of the mesh client. We develop an analytical model based on stochastic Petri net techniques for analyzing the performance of LMMesh and a computational procedure for calculating the overall network cost. Through a comparative performance study, we show that LMMesh outperforms both pure routing-based location management schemes and pure pointer forwarding schemes, as well as traditional tunnel-based location management schemes.**

***Index Terms*—Location management, routing-based location update, pointer forwarding, wireless mesh networks, performance analysis.**

I. Introduction

Wireless Mesh Networks (WMNs) are emerging as a promising solution for next-generation broadband wireless Internet access in recent years. A WMN consists of two types of nodes, namely, *mesh routers* (MRs) that have minimal mobility, and *mesh clients* (MCs) [1] that may be highly mobile. Each WMN has one or more *gateways* that are special MRs connected to the Internet. The set of MRs forms a *wireless mesh backbone* that routes network traffic and provides last-mile broadband Internet access to MCs. Because MCs may be highly mobile, mobility management is critical for the proper operation of the WMN. Mobility management consists of *location management* and *handoff management*. We focus on location management in this paper.

Location management has been researched intensively for cellular networks and Mobile IP-based wireless networks [2,3,4,5]. Existing schemes proposed for Mobile IP networks (e.g., [6,7,8,9,10,11,12,13,14]) and cellular networks (e.g., [15,16]), however, cannot be applied to WMNs without non-trivial modifications and performance penalty, due to significant differences in network characteristics. For example, those schemes rely on centralized management facilities, e.g., HLR/VLR in cellular networks and HA/FA in mobile IP networks, which do not exist in WMNs. Therefore, those schemes are not applicable to WMNs as argued in [1]. For a similar reason, location management protocols proposed for mobile ad hoc networks (MANETs) [17,18,19] are generally not applicable to WMNs. A fundamental difference between WMNs and MANETs is that WMNs have a quasi-static routing infrastructure consisting of MRs, whereas MANETs lack such an infrastructure.

In this paper, we propose LMMesh: a routing-based location management scheme with pointer forwarding for WMNs. LMMesh integrates routing-based location update and pointer forwarding into a single scheme that exploits the advantages of both methods, while avoiding their drawbacks. A well-known advantage of routing-based location update is that it enables the propagation of location information of MCs to the concerning parties using regular data packets originated from the MCs. This approach avoids the signaling overhead of explicit location update messages. Routing-based location update, however, does not work well for MCs that do not have active network sessions or MCs that are not sending data packets. Pointer forwarding is a solution for location management that uses explicit location update messages. It works for those MCs for which routing based location update does not work well, at the expense of additional signaling cost for the location update messages.

Although routing-based location update and pointer forwarding have been individually applied in many mobile communication networking studies, the integration of them and the impact of this integration on the overall network performance has not been studied. The contributions of this work are (a) we formulate the interaction between routing-based location update and pointer forwarding and analyze the impact of this integration on the overall network communication cost incurred; (b) we propose the design notion of optimal pointer forwarding when integrated with routing-based location update by dynamically identifying the optimal pointer forwarding chain length for each MC based on the MC's service and mobility characteristics to minimize the network communication cost; (c) we develop an analytical model based on stochastic Petri net [20] techniques for performance analysis. Through a comparative performance study, we show that LMMesh outperforms both pure routing-based location management schemes and pure pointer forwarding schemes, as well as traditional tunnel-based location management schemes.

The rest of this paper is organized as follows. Section II surveys related work and contrasts our work with existing

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work. Section III describes the system model of LMMesh and assumptions made in the paper. Section IV presents the proposed location management scheme. In Section V we develop a performance model to analyze the performance of LMMesh. Section VI presents numerical data to demonstrate the effectiveness of LMMesh and to compare its performance against existing location management schemes for WMNs. The paper concludes with Section VII.

II. Related Work

Existing mobility (location) management schemes can be classified largely into two categories: *tunnel-based* schemes and *routing-based* schemes [3]. Examples of tunnel-based mobility management schemes include Mobile IP [21], MIP-RR [12], HMIP [13], and IDMP [14] proposed for Mobile IP networks, and Ant [22] and M^3 [23] proposed for WMNs. The basic idea of tunnel-based schemes is that mobile hosts explicitly register or update their location information to some centralized location servers, e.g., *home agents* in Mobile IP or *gateway foreign agents* in MIP-RR, through location registration/update messages. Such messages incur significant signaling cost for highly mobile clients. This is particularly a severe problem if location registration/update messages are sent upon every location change. For example, in Ant, a location update message has to be sent to a central location server every time a mobile host changes its serving MR.

Routing-based schemes represent another class of mobility management schemes proposed for various types of IP-based networks. Typical examples of routing-based mobility management schemes include Cellular IP [24] and HAWAII [25] proposed for Mobile IP networks, and WMM [26], iMesh [27], MEMO [28], and the scheme in [29] proposed for WMNs. The basic idea of routing-based schemes is that mobility management is integrated with routing such that location information of mobile hosts can be propagated throughout the network through regular packet routing.

In Cellular IP, HAWAII, and WMM, in addition to routing tables, routers also maintain location caches that store location information of mobile hosts for which they have routed packets. One of the most distinct characteristics of these routing-based schemes is that data packets originated from a mobile host carry the current location information of the sender. Therefore, the location information of the mobile host kept in a router's location cache can be updated when the router processes data packets originated from the mobile host. In this way, the host-specific route of the mobile host is updated when it sends data packets.

Because the update of location information and the maintenance of host-specific routes in these routing-based schemes solely rely on packet routing, they are essentially opportunistic. Specifically, for idle mobile hosts that are not sending any data packets, their location information may become outdated and consequently their host-specific routes may become obsolete. This leads to a major performance deficiency of these routing-based schemes. LMMesh proposed in this paper uses pointer forwarding to solve the above problem, and at the same time, minimizes the overall network traffic incurred by mobility management and packet delivery.

TABLE I
Parameters and their physical meanings used in performance modeling and analysis.

Parameter	Physical meaning
σ	Mobility rate
$\lambda_{UI}/\lambda_{DI}$	Uplink/downlink Internet session arrival rate
$\lambda_{IL}/\lambda_{OL}$	Incoming/outgoing intranet session arrival rate
μ_I/μ_L	Internet/intranet session departure rate
$\lambda_{UIP}/\lambda_{DIP}$	Uplink/downlink packet arrival rate of Internet sessions
$\lambda_{ILP}/\lambda_{OLP}$	Incoming/outgoing packet arrival rate of intranet sessions
ω	Rate of reconnections to the WMN
α	Average number of hops between the gateway and an MR
β	Average number of hops between any two MRs
γ	Ratio of the Internet session arrival rate to the intranet session arrival rate
δ	Ratio of the average duration of Internet sessions to that of intranet sessions
ζ	$\frac{\lambda_{UIP}}{\lambda_{DIP}}$
τ	One-hop communication latency between two neighboring MRs
P_f/P_b	Probability that an MC moves forward/backward
P_g	Probability that an intranet packet is routed by the gateway
P_q	Probability that the location query procedure is executed in WMM
P_r	Probability that an MR broadcasts the route request message in WMM
N_{MR}	Number of MRs in a WMN

iMesh and MEMO are routing-based schemes based on routing protocols proposed for mobile ad hoc networks (OLSR [30] and AODV [31], respectively). Both schemes rely on broadcasting traffic for route discovery or location change notification, thus incurring excessive signaling overhead. LMMesh is routing-based in the sense that location information of MCs is propagated to the concerning parties using regular data packets originated from the MCs.

III. System Model

We consider a WMN in which there are multiple gateways connecting the WMN to the Internet. Each gateway covers a *zone* of the WMN and maintains a location database for MCs within the zone. For each MC, there exists an entry in the location database recording its current location information, which is the address of its forwarding chain head, i.e., the first MR on the chain. In this paper, we refer to the forwarding chain head as the *anchor MR* (AMR). With the address of an MC's AMR, the MC can be located by following the forwarding chain. Note that the AMR of an MC may be co-located with its current serving MR. The zones covered by different gateways do not overlap with each other, such that at any time, the location information of any MC is kept in the location database of the gateway within which it resides.

Table I lists the parameters and their physical meanings used in the following sections. We use a parameter called the *service to mobility ratio* (SMR) of each MC to depict the MC's mobility and service characteristics. For an MC with an average packet arrival rate denoted by λ_p and mobility rate denoted by σ, its SMR is defined by $\frac{\lambda_p}{\sigma}$. The physical meaning of mobility rate is the number of serving MR changes per time unit. An MC can dynamically monitor the packet arrival rate by counting the number of data packets arrived in a time interval and calculating the average number of data packets arrived per time unit. Similarly, an MC can dynamically count the number of serving MR changes in a time interval and calculate the average number of serving MR changes per time unit to obtain the mobility rate.

We assume that future mobile devices, e.g., smartphones, PDAs, tablet computers, etc., are powerful enough to execute the computational procedure developed in this paper at run-time to dynamically determine the optimal threshold for the forwarding chain length in LMMesh. For mobile devices that are less powerful in computation, an alternative table-lookup approach can be used to determine the optimal threshold in real time without having to execute the computational procedure. Specifically, the optimal threshold can be statically determined at the design time over a wide range of mobility and service characteristics and stored in a table for fast lookup. Then, during the execution of LMMesh, a simple table lookup can quickly determine the optimal threshold for an MC, based on the SMR of the MC.

As discussed in Nandiraju et al. [32], Internet traffic, i.e., the traffic between MRs and the gateway, dominates peer-to-peer traffic in WMNs because WMNs are expected mainly to be a solution for providing last-mile broadband Internet access. We use a parameter γ to represent the ratio of the Internet session arrival rate to the intranet session arrival rate, and another parameter δ to represent the ratio of the average duration of Internet sessions to the average duration of intranet sessions.

Internet traffic is also characterized by traffic asymmetry between the downlink and uplink [33,34]. Typically the traffic load on the downlink is much larger than the one on the uplink. Traffic asymmetry is especially pronounced for mobile multimedia applications, e.g., real-time video streaming, online radio, online games, etc. Due to traffic asymmetry. It is expected that the downlink packet arrival rate is much higher than the uplink packet arrival rate in mobile Internet applications. We use a parameter ζ to represent the ratio of the downlink packet arrival rate to the uplink packet arrival rate in Internet sessions.

IV. LMMESH

In this section, we present the proposed location management scheme, namely LMMesh. In Sections IV-A-IV-D we discuss the protocol behavior when a MC is within a gateway zone. In Section IV-E, we discuss the protocol behavior when a MC moves from one gateway zone to another. Finally in Section IV-F, we address the scalability of LMMesh.

A. Routing-based Location Update and Pointer Forwarding

In LMMesh, we allow every data packet (in an Internet or intranet session) originated from an MC to carry the up-to-date location information of the sender, i.e., the address of the MC's current serving MR, in the option field of the packet header. Upon receiving the data packet, a gateway (in an Internet session) or an intranet correspondence node (CN) of the MC (in an intranet session) extracts the location information from the data packet. The gateway uses this information to update the location database, and the intranet CN uses this information to route data packets to the MC. More specifically, for an Internet session between an MC and an Internet host, when receiving an uplink data packet from the MC, the gateway uses the location information carried by the data packet to update the location database. For an intranet session between two MCs in the same WMN, location information carried by data packets transmitted between the MCs is used by the serving MR of the receiver to update its routing table and to route data packets to the sender.

Routing-based location update works well for MCs that are actively sending data packets. For MCs that do not have active network sessions or MCs that are not sending data packets, however, routing-based location update does not work well. Even for MCs that are actively sending data packets, routing-based location update may not be a complete solution. For example, suppose that there is an intranet session between MC_1 and MC_2 in the same WMN, and that MC_1 continuously sends data packets to MC_2. Although MC_2 is continuously being updated with the up-to-date location information of MC_1, the gateway may not be updated because data packets from MC_1 to MC_2 may not go through the gateway. Now, suppose that an Internet host initiates a new Internet session towards MC_1. Upon receiving the session, the gateway may need to perform a costly location query procedure based on broadcasting, as in [26], to locate MC_1 before delivering the session.

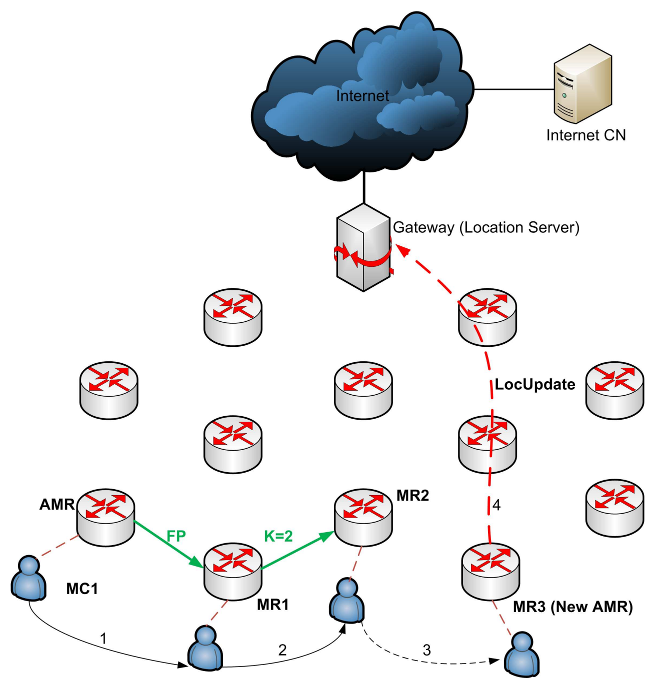

Fig. 1. The pointer forwarding method (*LocUpdate* means a location update message, and *FP* means a forwarding pointer).

To address those problems, LMMesh uses a per-user pointer forwarding method to complement routing-based location update. The basic pointer forwarding method [35] works as follows. When an MC moves from its current serving MR to a new MR, a location handoff is performed. If the length of the MC's current forwarding chain is less than a threshold K for the forwarding chain length, a new forwarding pointer is setup between the old MR and new MR, and the forwarding chain length is increased by one. The physical representation of a forwarding pointer kept by an MR is the address of the next MR along the forwarding chain. On the other hand, if the length of the forwarding chain is equal to K, no new forwarding pointer can be setup in this case. Instead, the movement triggers a location update, i.e., a location update message is sent to the gateway to update the MC's location information stored in the location database. After the location update, the forwarding chain is reset and the new serving MR becomes the new AMR of the MC. Note that the forwarding chain is also reset whenever the gateway receives a data packet from the MC that carries the address of the MC's current serving MR. Fig. 1 illustrates the pointer forwarding method using an example in which $K = 2$, described below:

1) When the MC moves from its current AMR, which is also its current serving MR, to MR1, a forwarding pointer is setup between its AMR and MR1 and the forwarding chain length is one;
2) The MC moves to MR2 after employing MR1 as its serving MR for some time, and a forwarding pointer is setup between MR1 and MR2 and the forwarding chain length becomes two;
3) The MC again moves, this time to MR3, after being associated with MR2 for some time. This third movement causes the forwarding chain being reset because $K = 2$;
4) MR3 becomes the MC's new AMR, and a location update message is sent to the gateway to update the MC's location information stored in the location database.

LMMesh takes a step further by dynamically determining the optimal threshold for the forwarding chain length that minimizes the overall communication cost for each individual MC, based on the MC's specific mobility and service characteristics. The overall communication cost we consider in this paper includes the signaling cost for location management and the service cost for packet delivery. The forwarding chain length of an MC significantly affects the overall communication cost incurred by the MC. Specifically, the longer the forwarding chain, the lower the location update rate, and consequently, the smaller the signaling overhead. However, the packet delivery cost increases as the forwarding chain becomes longer. Intuitively, there exists a trade-off between the signaling cost for location management and the service cost for packet delivery. LMMesh explores the tradeoff and dynamically determines the optimal threshold for the forwarding chain length that minimizes the overall communication cost on a per-user basis. In the remainder of the paper, we use K to denote the threshold, and $K_{optimal}$ to represent the optimal threshold. We show that the analytical model developed in this paper can be used to dynamically determine $K_{optimal}$, given parameters characterizing the specific mobility and service characteristics of an MC.

B. Integration and Its Impact

LMMesh uses both methods for location management in an integrated manner that achieves network cost minimization dynamically on a per-user basis. The integration takes the advantages of both methods, while avoiding their drawbacks. The use of routing-based location update has a positive effect of reducing the signaling traffic of explicit location update messages in pointer forwarding. The reason is that LMMesh relies less on the explicit location update messages in pointer forwarding for location management when an MC is actively sending data packets. On the other hand, when an MC does not have active network sessions or is not sending data packets, the use of pointer forwarding addresses the problems associated with routing-based location update, as discussed above. Particularly, the costly location query procedure based on broadcasting as in [26] is avoided by using the pointer forwarding method.

Essentially, LMMesh is adaptive to the changing mobility and service behaviors of an MC in the context of the integration. This adaption is the result of dynamically determining the optimal threshold $K_{optimal}$ for the forwarding chain length. The value of $K_{optimal}$ changes dynamically when the MC has service and mobility activities that vary over time. For example, when the rate at which the MC sends data packets is high, the value of $K_{optimal}$ of the MC tends to increase. Consequently, the rate at which location update messages are sent in pointer forwarding tends to decrease. This is because LMMesh relies less on the explicit location update messages for location management when an MC is actively sending data packets that also serve the purpose of implicit location update messages. These observations are demonstrated by the numerical results presented in Section VI.

C. Location Search Procedure

When a new Internet or intranet session is initiated towards an MC, LMMesh utilizes a location search procedure to locate the current serving MR of the MC before the session is delivered. By locating the current serving MR of the MC and consequently resetting the forwarding chain, the new session can be delivered directly to the MC following the shortest path, thereby reducing the packet delivery cost. The gain in the reduction of the packet delivery cost is particularly pronounced when the packet arrival rate to the MC is considerably high, compared with its mobility rate. Note that the location search procedure is only executed when a new session is initiated towards an MC.

1) Location Search for Internet Sessions: Fig. 2 illustrates the location search procedure for a new Internet session initiated towards an MC, which is described as follows:

1) When an Internet session initiated by an Internet host towards an MC arrives at the gateway, the gateway sends a location request message to the MC's current AMR (the gateway keeps the address of the MC's AMR in the location database);
2) The AMR forwards the message to the MC's current serving MR;

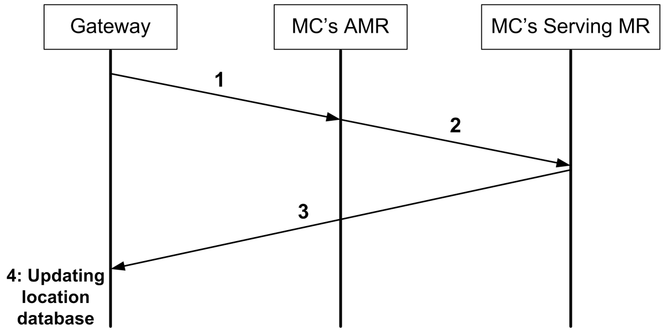

Fig. 2. The location search procedure for Internet sessions.

3) Upon receiving the location request message, the MC's current serving MR sends a location update message back to the gateway, making itself the new AMR of the MC;
4) The gateway updates the location information of the MC in the location database, and the location search procedure is completed.

After the location search procedure is completed, the MC's forwarding chain is reset and subsequent downlink Internet data packets from the Internet host to the MC will be routed to the new AMR. The gain is that the routing path is shortened, and the packet delivery cost is reduced.

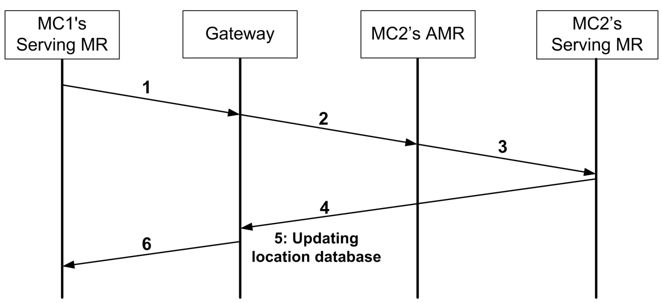

Fig. 3. The location search procedure for intranet sessions.

2) Location Search for Intranet Sessions: For an intranet session initiated by MC_1 towards MC_2, a location search procedure similar to the above is executed to locate the current serving MR (MR2) of MC2. Fig. 3 illustrates the procedure, described below:

1) When the current serving MR (MR1) of MC1 receives the intranet session request from MC1, it sends a location request message to the gateway;
2) The gateway forwards the message to MC2's current AMR;
3) The message is further forwarded to MR2 following the forwarding chain;
4) Upon receiving the location request message, MR2 sends a location update message back to the gateway;
5) The gateway updates the location information of MC2 in the location database;
6) The gateway also sends the updated location information of MC2 (the address of MC2's new AMR) to MR1, and the location search procedure is completed.

In this procedure, after the gateway receives the location update message, the current forwarding chain of MC2 is reset and MR2 becomes its new AMR. Subsequent data packets sent to MC2 will be routed to its new AMR.

D. Data Packet Routing

To route data packets to an MC in LMMesh, the address of the MC's current AMR must be known. This information is always kept in the location database on the gateway. It is also carried in the packet header of data packets originated from the MC (the address carried in this case is the one of the MC's current serving MR). Once the address of the MC's current AMR is known, routing data packets to the MC simply relies on the underlying routing protocol.

Specifically, in an Internet session, data packets sent from an Internet host to an MC always pass through the gateway, which routes them to the current AMR of the MC as recorded in the location database. The AMR forwards the data packets to the MC's current serving MR (if the AMR and current serving MR are not co-located), following the forwarding chain, and the serving MR finally delivers the packets to the MC. In an intranet session between two MCs, data packets sent between the MCs are first routed from the sender MC's current serving MR to the receiver MC's current AMR, which then forwards the packets to the receiver MC's current serving MR (if the receiver MC's AMR and serving MR are not co-located). The serving MR finally delivers the data packets to the receiver MC.

E. Multiple Gateways

When an MC moves from one zone to another, a gateway-level location handoff occurs to transfer the mobility management role from the gateway of the MC's current zone to that of its new zone.

Specifically, when the MC moves to a new zone, it first registers with the gateway of the new zone and obtain a new *gateway foreign address* (GFA), by sending a location binding update message to the gateway. When the gateway receives the message, it creates a new entry for the MC with the address of the MC's new AMR, which is the new serving MR of the MC in the new zone. The MC also sends a location binding update message to all its current intranet and Internet CNs such that future network traffic from these CNs to the MC will be routed towards the new gateway. Before the CNs are updated with the new GFA of the MC, however, they will send data packets to the MC's old gateway. To prevent those data packets from being lost, the MC sends its old gateway a location binding cancellation message carrying its new GFA. When the old gateway receives the message, it knows that the MC is registered with the new gateway and forwards data packets received from the MC's CNs towards the new gateway for the time period before the CNs are updated with the MC's new GFA. After the gateway-level location handoff, the MC executes LMMesh as described in Sections IV-A-IV-D for mobility management within the new zone.

When a gateway receives a request for the current location of an MC for which it cannot find an entry in its location database, the gateway broadcasts the request to all the other gateways. Upon receiving a reply from another gateway that has the current location information of the MC, the gateway sends the current location information of the MC, i.e., the address of the MC's current AMR to the requester. It is worth emphasizing that LMMesh can minimize the probability of such costly broadcasting traffic through the gateway-level location handoff procedure and the integration of routing-based location update and pointer forwarding.

F. Scalability of LMMesh

Scalability is an important requirement for a mobility management scheme for WMNs. LMMesh is a scalable solution for mobility management because it supports sharing of the mobility management role at both the gateway and MR levels in a hierarchical way such that a single gateway or MR will not become the bottleneck.

- Each gateway is only responsible for mobility management of MCs within the zone. The mobility management responsibility of a gateway for an MC is transferred to another gateway once the MC migrates to another zone. Therefore, given that gateways are typically placed in the WMN with load balancing principles (e.g., [36]), the gateways will evenly share the mobility management responsibility. No gateway would become the bottleneck.
- Within each zone, all MRs share the mobility management load by talking the role of either an AMR or a forwarding MR on the forwarding chain of an MC. Furthermore, because AMRs are dynamically selected by the MCs when they move, no MR would become the bottleneck by taking the role of an AMR.
- The benefit of minimizing the network communication cost on a per MC basis as a result of applying LMMesh is cumulative and proportional to the number of MCs. This design consideration makes LMMesh especially beneficial for large WMNs.

V. Performance Model

A. Analytical Model for LMMesh

In this section, we develop an analytical model based on stochastic Petri net (SPN) techniques for analyzing the performance of LMMesh. Fig. 4 shows the SPN model for LMMesh. The SPN model captures the dynamic service and mobility behavior of an MC using states and events. We choose SPN as the tool for performance modeling because: 1) an SPN model is a concise representation of the underlying Markov or semi-Markov chain that may have a large number of states; 2) an SPN model is capable of reasoning the behavior of an MC, as it migrates among states in response to system events.

An SPN model consists of entities such as transitions (e.g., *Move* and *Forward*), tokens, places (e.g., *Movement* and *FL*), and arcs that connect transitions and places. A transition is used to represent the firing of an event, and it can be either a timed transition (e.g., *Move* and *ResetLU*) or an immediate transition (e.g., *Forward* and *Backward*). A timed transition is fired after an event occurrence time is elapsed, while an immediately transition fires immediately. For example, an MC moves to a new MR (modeled by firing transition *Move*) after being associated with its current serving MR for an amount of time that is exponentially distributed. A token is used as a marker; it is used here to represent an event occurrence. For example, a new token is put into place *Movement* when *Move* is fired. A place is a token holder to contain tokens which represent the number of event occurrences. For example, the number of tokens in place *FL* is used to represent the forwarding chain length. Finally, an output arc connects a transition to a place and an input arc connects a place to a transition. An arc is associated with a multiplicity defining the number of tokens that will be moved into the output place (if it is an output arc) or moved out of the input place (if it is an input arc). For example, the arc that connects place *FL* to transition *ResetLU* has a multiplicity of K. This means that when transition *ResetLU* fires, it consumes K tokens from place *FL*.

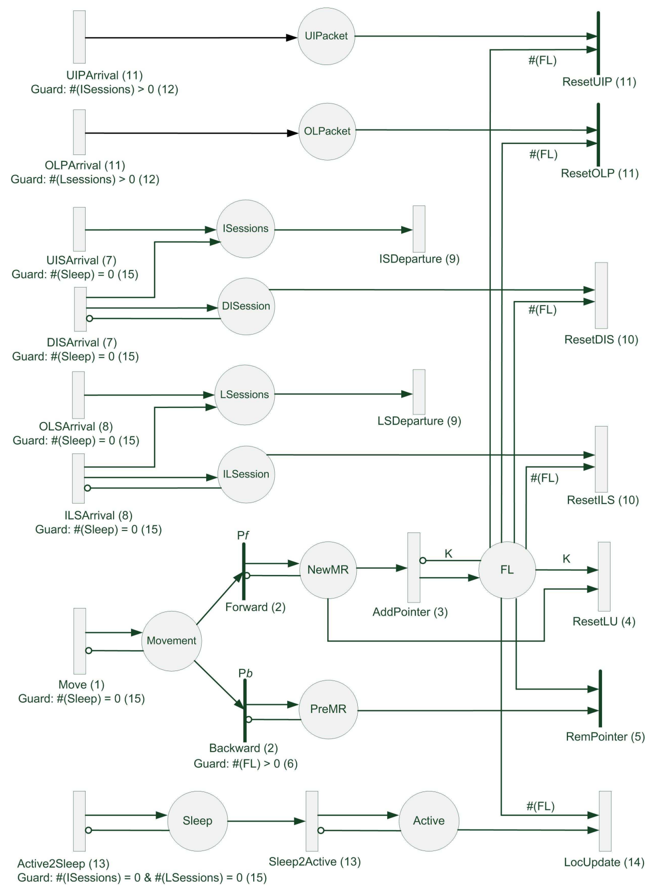

Fig. 4. The SPN model for LMMesh.

In Fig. 4 we put in numbers in parenthesis to label the SPN model sequence. The SPN model for LMMesh is constructed as follows:

1) The movement of an MC is modeled by transition *Move*, the transition rate of which is σ. When the MC moves to a new MR, thus incurring a location handoff, a new token is put into place *Movement*, indicating that the location handoff is completed.
2) The MC may move forward to a new MR, or move

backward to the most recently visited MR. The SPN model differentiates between these two cases using two immediate transitions *Forward* and *Backward*. Probabilities P_f and P_b associated with *Forward* and *Backward* depend on the network coverage model, which will be introduced in Section V-B.

3) If the MC moves forward to a new MR, transition *Forward* is fired and a new token is put into place *NewMR*. If the current forwarding chain length is smaller than K, a new forwarding pointer needs to be setup. This is modeled by firing transition *AddPointer*, if the number of tokens in place *FL* is less than K. *FL* represents the current forwarding chain length.
4) If the number of tokens in place *FL* is already equal to K, a new forward movement triggers a location update and the forwarding chain is reset. This is modeled by firing transition *ResetLU*, when there are K tokens in place *FL* and one token in place *NewMR*. The firing of *ResetLU* consumes all tokens in place *FL*, representing that the forwarding chain is reset.
5) If the MC moves backward to the most recently visited MR, transition *Backward* is fired and a token is put into place *PreMR*. This will subsequently enable and fire immediate transition *RemPointer*. We use an immediate transition to model the event of removing a forwarding pointer because the pointer will be purged automatically upon timeout.
6) Notice that it is only reasonable for the MC to move backward, when the forwarding chain length is not zero. This is modeled by associating an enabling function (`#(FL) > 0`) with transition *Backward*.
7) The arrival of a new uplink Internet session initiated by the MC is modeled by firing transition *UISArrival*, the transition rate of which is λ_{UI}. Accordingly, the arrival of a new downlink Internet session towards the MC is modeled by transition *DISArrival*, the transition rate of which is λ_{DI}.
8) The arrival of a new outgoing intranet session initiated by the MC is modeled by firing transition *OLSArrival*, the transition rate of which is λ_{OL}. Accordingly, the arrival of a new incoming intranet session towards the MC is modeled by transition *ILSArrival*, the transition rate of which is λ_{IL}.
9) Transitions *ISDeparture* and *LSDeparture* are used to model Internet session departure and intranet session departure, respectively.
10) The arrival of a new session towards the MC triggers the location search procedure and causes its current forwarding chain to be reset. This is modeled by firing transition *ResetDIS* for a newly arrived downlink Internet session or *ResetILS* for a newly arrived incoming intranet session. In either case, all tokens in place *FL* are consumed, modeling that its current forwarding chain is reset.
11) The location information of the MC stored in the location database is also updated when the gateway receives from the MC an uplink Internet data packet or an intranet data packet that is to be forwarded by the gateway. The arrival of these two kinds of data packets is modeled by transitions *UIPArrival* and *OLPArrival*, respectively. The events of updating the location database in these two cases are modeled by firing immediate transitions *ResetUIP* and *ResetOLP*. The firing of *ResetUIP* or *ResetOLP* consumes all tokens in place *FL*, representing that the current forwarding chain is reset.
12) It is only possible for the MC to send data packets when it has on-going Internet or intranet sessions. This is modeled by associating enabling functions as shown in the SPN model with transitions *UIPArrival* and *OLPArrival*.
13) The MC switches alternatively between active mode and sleep (idle) mode. Initially the MC is in active mode, and can send and receive data packets. After staying in active mode for a period of time, the MC switches to sleep mode to save battery life. This is modeled by firing transition *Active2Sleep* and putting a token into place *Sleep*. The transition rate of *Active2Sleep* is ω_s. When the MC is in sleep mode, it will not incur any network communication activities. The MC wakes up after being in sleep mode for some time. This is modeled by firing transition *Sleep2Active* and putting a token into place *Active*. The transition rate of *Sleep2Active* is ω_w.
14) When the MC wakes up and reconnects to the WMN, it sends a location binding update message to the gateway. This event is modeled by firing transition *LocUpdate*.
15) We assume that the MC switches to sleep mode only when it has no on-going sessions. This is modeled by associating a enabling function with transition *Active2Sleep*. When the MC is in sleep mode, it will not have any network activities and will not incur any location handoff. This condition is modeled by associating enabling functions with transitions *DISArrival*, *UISArrival*, *OLSArrival*, *ILSArrival*, *UIPArrival*, *OLPArrival*, and *Move*.

B. *Parameterization*

Transition *AddPointer* models the event of setting up a forwarding pointer. In this case, a round-trip message exchange between two involving MRs is carried out, thus the communication cost is 2τ. The transition rate is the reciprocal of the communication delay, i.e.,

$$\mu_{AddPointer} = \frac{1}{2\tau} \tag{1}$$

Transition *ResetLU* models the event of resetting the forwarding chain of an MC during a location update. This involves a round-trip message exchange between the gateway and the MC's current serving MR. The signaling cost incurred is $2\alpha\tau$. Thus, the transition rate is:

$$\mu_{ResetLU} = \frac{1}{2\alpha\tau} \tag{2}$$

Transition *ResetIS* models the event of resetting the forwarding chain of an MC due to the arrival of a new Internet session. Let i denote the length of the current forwarding chain of an MC. As elaborated in Section IV-C1, the communication cost in this case is $(2\alpha + i) \times \tau$. Thus, the transition rate is:

$$\mu_{ResetIS} = \frac{1}{(2\alpha + i) \times \tau} \tag{3}$$

Transition *ResetLS* models the event of resetting the forwarding chain of an MC due to the arrival of a new intranet session. As elaborated in Section IV-C2, the communication cost in this case is $(4\alpha + i) \times \tau$. Thus, the transition rate is:

$$\mu_{ResetLS} = \frac{1}{(4\alpha + i) \times \tau} \tag{4}$$

Transition *LocUpdate* models the event of sending the gateway a location binding update message when an MC wakes up and reconnects. The gateway replies with a location binding confirmation message as an acknowledgment. The signaling cost incurred is $2\alpha\tau$. Thus, the transition rate is:

$$\mu_{LocUpdate} = \frac{1}{2\alpha\tau} \tag{5}$$

Transition *UIPArrival* models the arrival of uplink Internet data packets originated from an MC at the gateway. The transition rate of *UIPArrival* is the effective rate of uplink Internet data packets originated from the MC, which can be calculated as follows:

$$\mu_{UIPArrival} = mark(ISessions) \times \lambda_{UIP} \tag{6}$$

where $mark(ISessions)$ returns the number of tokens in place *ISessions*, i.e., the number of on-going Internet sessions of the MC.

The arrival of outgoing intranet data packets originated from an MC at the gateway is modeled by transition *OLPArrival*. The transition rate of *OLPArrival* is the effective rate of outgoing intranet data packets originated from the MC arriving at the gateway, which can be calculated as:

$$\mu_{OLPArrival} = P_g \times mark(LSessions) \times \lambda_{OLP} \tag{7}$$

where P_g is as defined in Table I, and $mark(LSessions)$ represents the number of on-going intranet sessions.

The transition rates of *ISDeparture* and *LSDeparture* are effective departure rates of Internet and intranet sessions, respectively. We use a $M/M/\infty$ queue to model the process of session arrivals towards an MC. Using the $M/M/\infty$ queuing model, the transition rates of *ISDeparture* and *LSDeparture* can be derived as follows:

$$\begin{aligned} \mu_{ISDeparture} &= mark(ISessions) \times \mu_I \\ \mu_{LSDeparture} &= mark(LSessions) \times \mu_L \end{aligned} \tag{8}$$

Following the assumptions made in Section III, the outgoing and incoming intranet session arrival rates and the uplink Internet packet arrival rate can be calculated as follows:

$$\begin{aligned} \lambda_{OL} &= \tfrac{\lambda_{UI}}{\gamma} \\ \lambda_{IL} &= \tfrac{\lambda_{DI}}{\gamma} \\ \lambda_{UIP} &= \tfrac{\lambda_{DIP}}{\zeta} \end{aligned} \tag{9}$$

In this paper, we assume the square-grid mesh network model for WMNs [37] and the random walk model for MCs. For the square-grid mesh network model, we assume that all MRs have the same wireless range that covers direct neighboring MRs located in four orthogonal directions. Under these models, each MR has four direct neighbors and an MC can move randomly from the current MR to one of the MR's neighbors with equal probability, i.e., $1/4$. Thus, we have:

$$P_f = \frac{3}{4}, P_b = \frac{1}{4} \tag{10}$$

An MC typically switches alternatively between active mode and sleep mode during its stay in a WMN. The rate of reconnection denoted by ω can be derived as follows:

$$\omega = \frac{\omega_w \times \omega_s}{\omega_w + \omega_s} \tag{11}$$

C. Performance Metrics

We use the total communication cost incurred per time unit as the metric for performance evaluation and analysis. It is worth noting that because the total communication cost is a per time unit measure, the accumulative effect of even a small cost difference will be significant.

The total communication cost incurred per time unit by LMMesh consists of the signaling cost of location handoff and update operations, the signaling cost of location tracking operations, the signaling cost of location binding update upon reconnection, and the packet delivery cost. Let C_{LMMesh} denote the total communication cost incurred per time unit by LMMesh, and let $C_{location}$, $C_{tracking}$, $C_{reconnection}$, and $C_{delivery}$ denote the cost components, respectively. Subscripts "I" and "L" denote Internet and intranet sessions, respectively. Using these cost terms, C_{LMMesh} is calculated as follows:

$$\begin{aligned} C_{LMMesh} &= C_{location} \times \sigma' + C_{tracking,I} \times \lambda'_{DI} \\ &+ C_{tracking,L} \times \lambda'_{IL} + C_{delivery,I} \times \lambda'_{DIP} \\ &+ C_{delivery,L} \times \lambda'_{ILP} + C_{reconnection} \times \omega \end{aligned} \tag{12}$$

In the above equation, σ' represents the steady-state effective mobility rate. λ'_{DI} and λ'_{IL} represent the steady-state effective downlink Internet session arrival rate and incoming intranet session arrival rate, respectively. λ'_{DIP} and λ'_{ILP} denote the steady-state aggregate downlink Internet packet arrival rate and incoming intranet packet arrival rate, respectively. The first three rates are "effective" rates to account for the fact that when an MC is in sleep mode it will not incur network communication activities, and they can be calculated by:

$$\begin{aligned} \sigma' &= (1 - P_{Sleep}) \times \sigma \\ \lambda'_{DI} &= (1 - P_{Sleep}) \times \lambda_{DI} \\ \lambda'_{IL} &= (1 - P_{Sleep}) \times \lambda_{IL} \end{aligned} \tag{13}$$

where P_{Sleep} is the steady state probability that the MC is in sleep and is calculated by $E[mark(Sleep)]$ where $E[X]$ stands for the expected value of X. The last two rates are "aggregate" rates to account for the fact that an MC may be simultaneously engaged in multiple Internet or intranet sessions and they can be calculated by:

$$\begin{aligned} \lambda'_{DIP} &= E[mark(ISessions)] \times \lambda_{DIP} \\ \lambda'_{ILP} &= E[mark(LSessions)] \times \lambda_{ILP} \end{aligned} \tag{14}$$

The stochastic model underlying the SPN model shown in Fig. 4 is a continuous-time Markov chain. Let P_i denote the probability that the underlying Markov chain is found in a state that the current forwarding chain length is i. Let S denote the set of states in the underlying Markov chain. Then $C_{location}$ can be calculated as follows:

$$C_{location} = \sum_{S} P_i C_{i,location} \tag{15}$$

where $C_{i,location}$ is calculated as:

$$C_{i,location} = \begin{cases} 2\tau & \text{if } 1 \leq i < K \\ 2\alpha\tau & \text{if } i = K \end{cases} \tag{16}$$

The location tracking cost $C_{tracking}$ can be calculated as follows:

$$C_{tracking} = \sum_{S} P_i C_{i,tracking} \tag{17}$$

where $C_{i,tracking}$ is either $C_{i,tracking,I}$ or $C_{i,tracking,L}$. The equations for calculating $C_{i,tracking,I}$ and $C_{i,tracking,L}$ are shown as follows:

$$\begin{aligned} C_{i,tracking,I} &= (2\alpha + i) \times \tau \\ C_{i,tracking,L} &= (4\alpha + i) \times \tau \end{aligned} \tag{18}$$

The packet delivery cost $C_{delivery}$ is derived in a similar way as follows:

$$C_{delivery} = \sum_{S} P_i C_{i,delivery} \tag{19}$$

where $C_{i,delivery}$ is either $C_{i,delivery,I}$ or $C_{i,delivery,L}$. $C_{i,delivery,I}$ and $C_{i,delivery,L}$ can be calculated as follows:

$$\begin{aligned} C_{i,delivery,I} &= (\alpha + i) \times \tau \\ C_{i,delivery,L} &= \beta\tau \end{aligned} \tag{20}$$

Intranet sessions in WMNs, which involve two peers interacting with each other bi-directionally, usually have similar packet arrival rates in both directions. It indicates that the location information of each peer stored by the serving MR of the other peer is updated in a similar rate. Thus, data packets sent and received between the two peers usually travel the same distance β on the average. The delivery cost of intranet data packets denoted by $C_{delivery,L}$ is therefore $\beta\tau$.

As analyzed above when deriving the transition rate of transition *LocUpdate*, $C_{reconnection}$ can be derived as follows:

$$C_{reconnection} = 2\alpha\tau \tag{21}$$

The computational procedure outlined above can be easily implemented by associating the SPN model with reward functions and calculating the steady-state rewards, using the SPNP [20] package.

VI. Performance Analysis

In this section, we analyze the performance of LMMesh, in terms of the total communication cost incurred per time unit. We also carry out a comparative performance study to compare LMMesh with MIP-RR [12], a tunnel-based scheme, WMM [26], a pure routing-based scheme, and a pure pointer forwarding scheme called the *dynamic anchor* scheme [40]. In the following, SMR is defined as SMR = $\frac{\lambda_{DIP}+\lambda_{ILP}}{\sigma}$. Unless explicitly stated, λ_{DIP} and λ_{UIP} are fixed, while σ is varied, i.e., SMR is inversely proportional to σ. The value of SMR varies from 8 to 256 in the analysis to account for the diversity of MCs in terms of service and mobility characteristics, and meanwhile ensures that the results are reasonably clear and representative. Table II lists the parameters and their default values used in the performance evaluation. The values of γ and δ are chosen in accordance with the assumptions made in Section III. The default value of ζ is chosen to be 10 because it is observed that the average ratio of the traffic load on the downlink to that on the uplink is 10 in web services [38]. The unit of time is *second* in this paper. The values of P_q and P_r are chosen according to their representative values presented in [26] and [39], respectively. All costs presented below are normalized with respect to $\tau = 1$.

TABLE II
Parameters and their default values.

Parameter	Value	Parameter	Value	Parameter	Value
γ	100	δ	10	ζ	10
λ_{UI}	$\frac{1}{600}$	λ_{DI}	$\frac{1}{600}$	μ_I	$\frac{1}{300}$
τ	1	α	30	β	30
ω_w	$\frac{1}{900}$	ω_s	$\frac{1}{1800}$	P_f/P_b	$\frac{3}{4}/\frac{1}{4}$
P_g	10.0%	P_q	5.0%	P_r	50.0%

A. Performance Evaluation of LMMesh

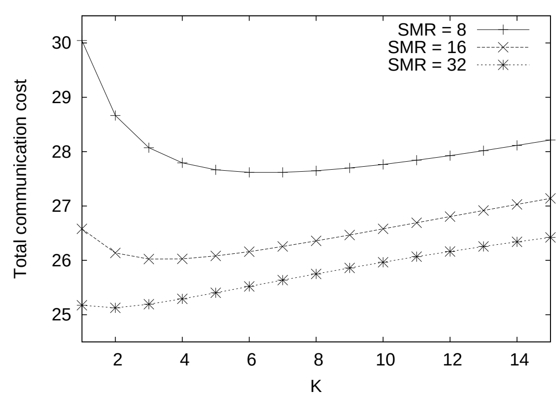

Fig. 5. Cost vs. K.

Fig. 5 shows C_{LMMesh} as a function of K, under different SMRs. The figure demonstrates that there exists an optimal threshold $K_{optimal}$ that minimizes C_{LMMesh}. It can be observed in the figure that C_{LMMesh} increases as SMR decreases. This is because as σ increases (recall that SMR is inversely proportional to σ), the signaling cost incurred by location management increases, and, consequently, C_{LMMesh} increases as well.

Fig. 6 plots $K_{optimal}$ as a function of SMR. It can be observed in the figure that $K_{optimal}$ decreases as SMR increases. The reason is that as σ becomes lower, allowing a shorter forwarding chain is favorable in order to reduce the packet delivery cost and thus the total communication cost.

Fig. 7 illustrates C_{LMMesh} as a function of ζ, under different SMRs. ζ is a critical system parameter as it largely determines the rate of data packet arrivals at the gateway, and accordingly the rate of location update by data packets. As can be seen in the figure, C_{LMMesh} increases monotonically as ζ increases. Given a fixed downlink Internet packet arrival rate λ_{DIP}, the rate of data packet arrival at the gateway

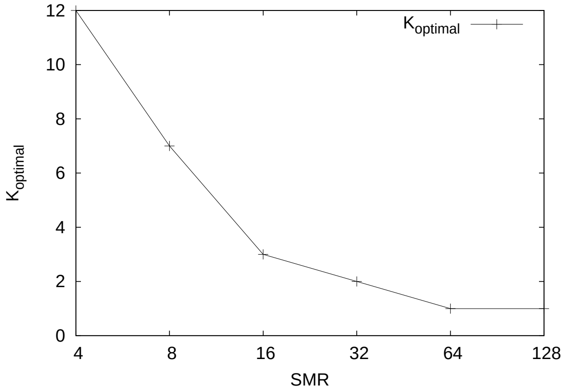

Fig. 6. $K_{optimal}$ vs. SMR.

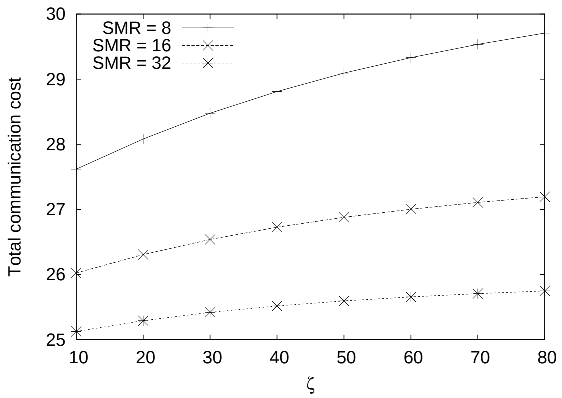

Fig. 7. Cost vs. ζ.

and accordingly the rate of location update by data packets decrease as ζ increases. The result is that the expected steady-state forwarding chain length and consequently C_{LMMesh} increase as ζ increases. This is justified by Fig. 8, which shows the steady-state average forwarding chain length as a function of ζ.

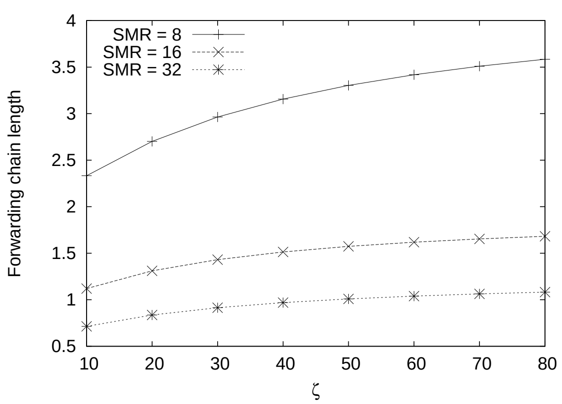

Fig. 8. Average forwarding chain length vs. ζ.

Fig. 9 investigates the effect of the *active ratio* on the performance of LMMesh. The active ratio of an MC is defined as ω_w/ω_s in the paper. In the analysis, ω_s is fixed, while ω_w is varied, i.e., the active ratio is proportional to ω_w. It can be observed in Fig. 9 that C_{LMMesh} increases monotonically with increasing active ratio. This is because a larger C_{LMMesh}

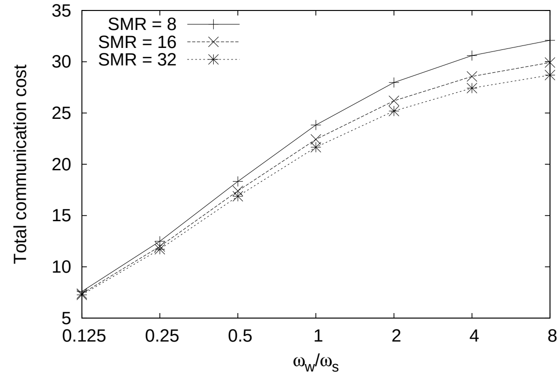

Fig. 9. Cost vs. ω_w/ω_s.

is incurred as an MC spends more time in active mode.

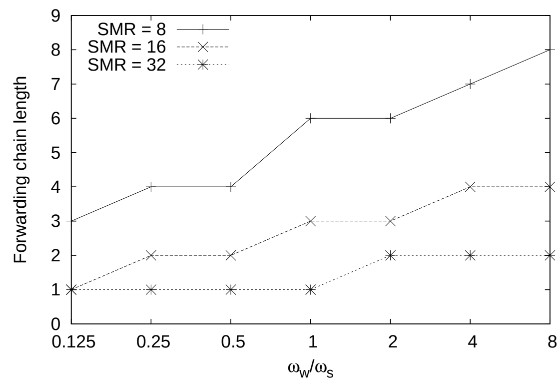

Fig. 10. $K_{optimal}$ vs. ω_w/ω_s.

Fig. 10 plots $K_{optimal}$ as a function of the active ratio, under different SMRs. As illustrated in the figure, $K_{optimal}$ is a monotonic function of the active ratio. The reason is that as ω_w increases, the rate of forwarding chain reset due to location tracking increases. Thus $K_{optimal}$ increases accordingly to ensure that C_{LMMesh} is minimized.

B. Performance Comparison

In this section, we compare LMMesh with MIP-RR [12], WMM [26], and the dynamic anchor scheme [40]. Here we first note that the extra cost of informing a MC's new GFA to all Intranet and Internet CNs upon a gateway-level handoff would be the same for all protocols. Also for Intranet traffic resulting from two MCs in two separate gateway zones, the extra cost for the source MC to route packets to the destination MC through the destination MC's gateway would be the same for all protocols. Consequently, it suffices to compare protocol performance based on the cost incurred while an MC is within a gateway zone. MIP-RR is a micro-mobility management scheme that aims at reducing the global location handoff signaling overhead and latency by performing location registrations locally within the service region of a regional mesh router (RMR). Specific to the use of MIP-RR in WMNs, each RMR runs on an MR and handles location changes of MCs locally within its service region. Whenever an MC moves to a new MR within the fixed service region of a RMR, it informs the RMR of its location change. When the MC moves from the service region of its current RMR to that of a new RMR, it informs the gateway and all its intranet correspondence nodes of the change in RMR. Because the service region of a RMR is fixed, we can use a threshold D of the distance between the RMR and any MR within its service region to model its service region boundary. An MC is considered moving outside of the service region of its RMR when the distance between its serving MR and the RMR exceeds the threshold. The dynamic anchor scheme is a pure pointer forwarding scheme that dynamically determines the optimal threshold of the forwarding chain length. WMM is a pure routing-based mobility management scheme with opportunistic location updates through packet routing. We demonstrate that LMMesh outperforms all three schemes. It is worth emphasizing that because the total communication cost is on a per time unit bases, even a small performance gain of 5% to 10% will be significant over time.

The total communication cost incurred per time unit by WMM consists of the signaling cost of location handoff operations, the signaling cost of location queries upon reconnection, and the packet delivery cost. Let C_{wmm} denote the total communication cost incurred per time unit by WMM. Then C_{wmm} is calculated as:

$$\begin{aligned} C_{wmm} &= C_{location} \times \sigma' + C_{delivery,I} \times \lambda'_{DIP} \\ &+ C_{delivery,L} \times \lambda'_{ILP} + P_q \times C_{query} \times \omega \end{aligned} \quad (22)$$

Because LMMesh and WMM essentially share the same characteristics for packet routing, the equations for calculating $C_{delivery,I}$ and $C_{delivery,L}$ are the same as those presented in Section V-C. In WMM, the signaling cost of the location registration procedure is calculated as: $C_{location} = 2\tau$. When an MC's current serving MR is unknown in WMM, a location query procedure is executed by the gateway by broadcasting a route request message to all MRs. The current serving MR of the MC replies to the gateway a route response message. The signaling cost of the location query procedure denoted by C_{query} is therefore the sum of the cost of broadcasting the route request message and the cost of transmitting the route response message, which is $\alpha\tau$.

We define the cost of broadcasting a route request message as the number of broadcasts required to deliver the message to all MRs, instead of the sum of one-hop transmission costs, because of the broadcasting nature of wireless transmission. We assume that a flooding algorithm based on *self-pruning* [39] is used for broadcasting in WMNs. Using such an algorithm, each node will rebroadcast a flooding packet no more than once. Thus, the number of broadcasts required to deliver the message to all MRs, can be calculated as: $P_r \times N_{MR}$. Therefore, we have $C_{query} = P_r \times N_{MR} + \alpha\tau$.

We assume the square-grid mesh network model for WMNs in the paper. In such a mesh network, the average distance between two arbitrary nodes, denoted by β, can be derived using the approach proposed in [41], given the dimension of the mesh network. It indicates that we can obtain the dimension of the mesh network by reversely applying the approach, given β. The detailed calculations are shown as follows:

$$\beta = \frac{2M}{3} \Rightarrow N_{MR} = M^2 = (\frac{3\beta}{2})^2 \quad (23)$$

where M denotes the dimension of the mesh network.

For the dynamic anchor scheme, the total communication cost incurred per time unit can be expressed using Equation 12, with the additional cost for an MC to inform its CNs when its location information stored in the location database is updated and its forwarding chain is reset. Accordingly, some equations presented in Section V-C need to be revised as follows:

$$C_{i,location} = \begin{cases} 2\tau & \text{if } 1 \leq i < K \\ (2\alpha + 2N_L\beta) \times \tau & \text{if } i = K \end{cases} \quad (24)$$

$$\begin{aligned} C_{i,tracking,I} &= (2\alpha + 2N_L\beta + i) \times \tau \\ C_{i,tracking,L} &= (4\alpha + 2N_L\beta + i) \times \tau \\ C_{i,delivery,L} &= (\beta + i) \times \tau \end{aligned} \quad (25)$$

where N_L denotes the number of active intranet correspondence nodes.

MIP-RR is essentially equivalent to the dynamic anchor scheme with a fixed threshold D and without the location tracking mechanism. Additionally, because the location handoff/update operations in MIP-RR are different from those in the dynamic anchor scheme, which is a pointer forwarding scheme, the equation shown below is different from the one above.

$$C_{i,location} = \begin{cases} 2i\tau' & \text{if } 1 \leq i < D \\ (2\alpha + 2N_L\beta) \times \tau' & \text{if } i = D \end{cases} \quad (26)$$

where i denotes the distance between the MC's current serving MR and its GFA in this case, and τ' is calculated as $\tau' = (1 + \epsilon) \times \tau$, where ϵ denotes the percentage of increase in τ due to the additional IP encapsulation/decapsulation overhead in tunnel-based schemes. Below we let $D = 4$ to evaluate the performance of MIP-RR.

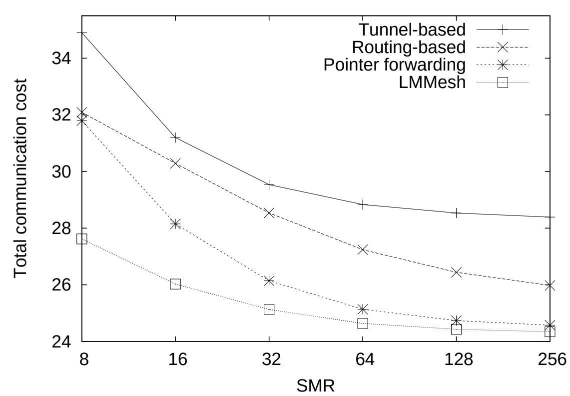

Fig. 11. Performance comparison: cost vs. SMR.

Fig. 11 compares the total communication cost incurred per time unit by the four schemes as a function of SMR. As can be seen in the figure, LMMesh significantly outperforms the other three schemes, namely, WMM (labeled as "routing-based"), dynamic anchor (labeled as "pointer forwarding"), and MIP-RR (labeled as "tunnel-based"), especially when SMR is small. The advantage of LMMesh is due to the

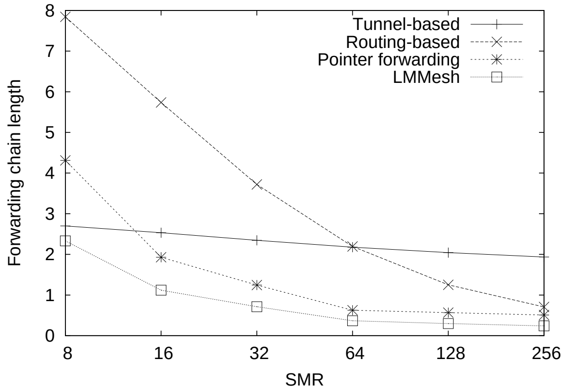

Fig. 12. Performance comparison: average forwarding chain length vs. SMR.

combination of routing-based location information update and pointer forwarding which eliminates the problem of opportunistic location updates. As expected, tunnel-based MIP-RR shows the worst performance because of its use of a rigid GFA service region size for all MCs that leads to suboptimal overall performance and the extra overhead introduced by packet encapsulation/decapsulation. Fig. 12 compares the average forwarding chain length as a function of SMR among the four schemes. As can be seen in Fig. 12, WMM due to its opportunistic nature has a much larger forwarding chain length than the dynamic anchor scheme and LMMesh over a wide range of SMR. Because a larger forwarding chain length means a higher per time unit packet delivery cost, this figure explains why WMM performs worse than the dynamic anchor scheme and LMMesh.

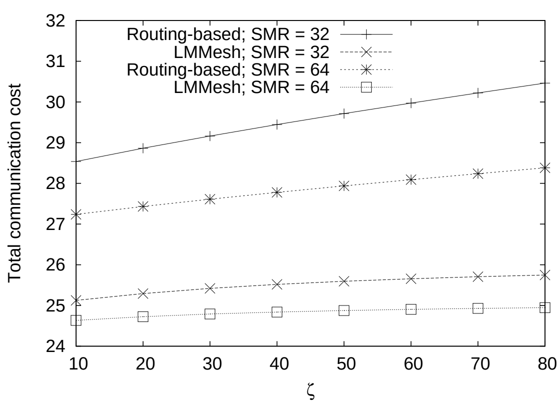

Fig. 13. Performance comparison: cost vs. ζ.

Fig. 13 compares the total communication cost incurred per time unit by two routing-based schemes, namely, LMMesh and WMM, as a function of ζ. As expected, the total communication cost increases monotonically with increasing ζ in both schemes. However, C_{wmm} increases much faster than C_{LMMesh}. This indicates that the impact of the rate of data packet arrivals at the gateway on the total communication cost is much more significant in WMM than in LMMesh because location information is updated primarily by uplink Internet data packets in WMM. This observation is well supported by Fig. 14, which compares the average forwarding chain length as a function of ζ between LMMesh and WMM. As

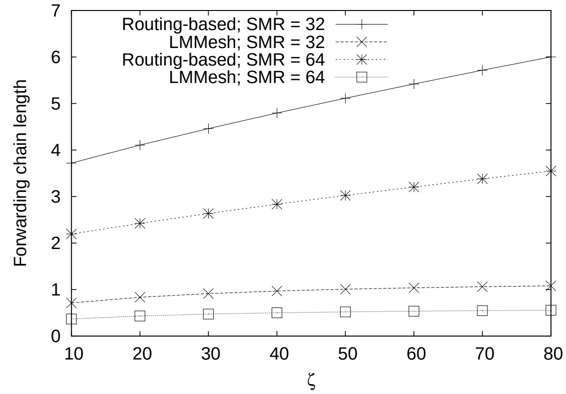

Fig. 14. Performance comparison: average forwarding chain length vs. ζ.

can be seen in the figure, the average forwarding chain length of WMM increases much faster than that of LMMesh with increasing ζ.

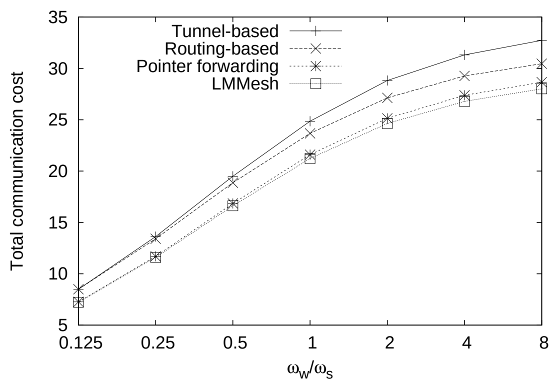

Fig. 15. Performance comparison: cost vs. ω_w/ω_s.

Fig. 15 compares the total communication cost incurred per time unit as a function of the active ratio among the four schemes. As expected, the total communication cost incurred by each of the four schemes increases monotonically as the active ratio increases. LMMesh again outperforms the other three schemes.

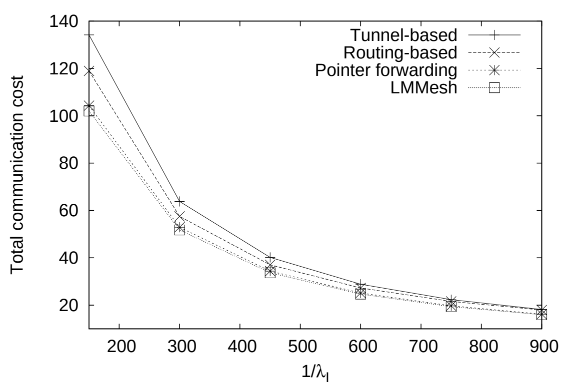

Fig. 16. Performance comparison: cost vs. λ_I.

Fig. 16 and Fig. 17 compare the total communication cost incurred per time unit by the four schemes, as a function of

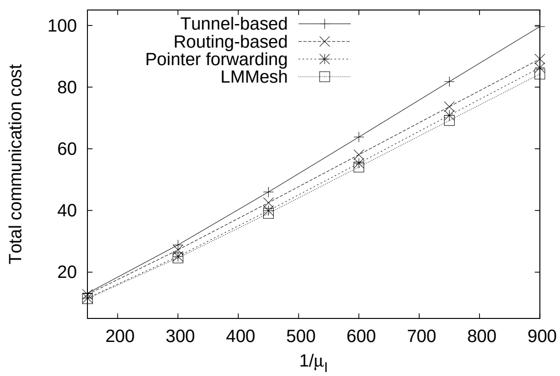

Fig. 17. Performance comparison: cost vs. μ_I.

$1/\lambda_I$ and $1/\mu_I$, respectively. It can be seen in the figures that the total communication cost incurred per time unit by each of the four schemes decreases monotonically with decreasing λ_I, whereas it increases monotonically with decreasing μ_I. This is because when μ_I is fixed and λ_I decreases, the average number of on-going sessions of each MC decreases accordingly. Conversely, when λ_I is fixed and μ_I decreases, the average number of on-going sessions of each MC increases. As shown in both figures, LMMesh outperforms the other three schemes.

C. Sensitivity Analysis

In this section, we investigate the sensitivity of the above analytical results with respect to the network coverage model assumed. Specifically, in the following analysis, a hexagonal network coverage model is used instead of the square-grid mesh model. In the hexagonal network coverage model, the coverage area of each MR is called a cell, and each MR has six direct neighbors. An MC can move randomly from an MR to one of its direct neighbors with the same probability. Thus, $P_f = \frac{5}{6}$ and $P_b = \frac{1}{6}$, under the hexagonal network coverage model.

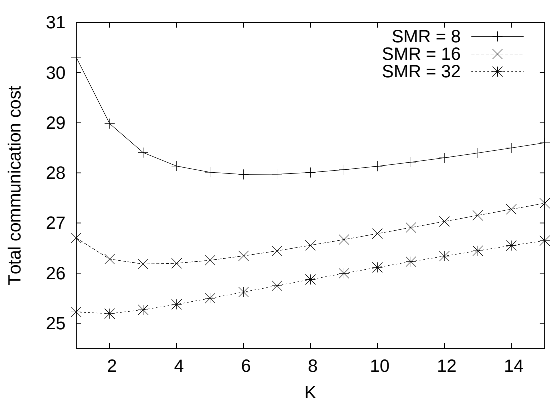

Fig. 18. Cost vs. K under the hexagonal network coverage model.

Fig. 18 illustrates C_{LMMesh} as a function of K, under the hexagonal network coverage model. It can be observed that cost curves shown in this figure and Fig. 5 exhibit high similarity in shape. The same conclusion can be drawn by comparing Fig. 19 with Fig. 11. Based on these observations, we can draw the conclusion that analytical results obtained are valid and are not sensitive to the network coverage model.

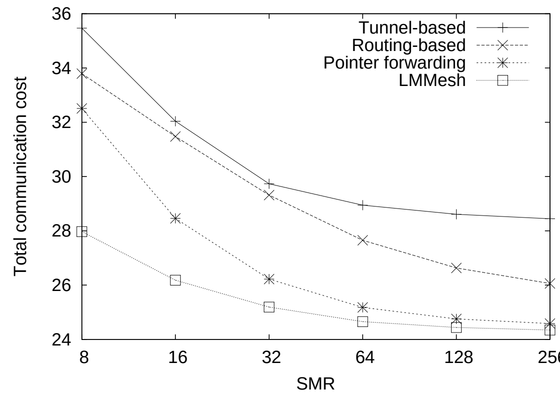

Fig. 19. Performance comparison: cost vs. SMR under the hexagonal network coverage model.

VII. Conclusion

In this paper, we proposed and analyzed a routing-based location management scheme with pointer forwarding, namely LMMesh, for wireless mesh networks. LMMesh integrates routing-based location update and pointer forwarding into a single scheme that exploits the advantages of both methods, while avoiding their drawbacks. LMMesh integrates these two methods to offer a complete solution to location management in wireless mesh networks, and considers the effect of the integration on the overall network cost incurred by location management and packet delivery. The tradeoff between the signaling cost for location management and the service cost for packet delivery is explored by LMMesh by dynamically determining the optimal threshold for the forwarding chain length that minimizes the overall network cost. LMMesh is optimal on a per-user basis and is adaptive to the changing mobility and service behaviors of an MC, as the optimal forwarding chain length is dynamically determined for the MC based on its mobility and service characteristics. LMMesh can be used in either single-gateway or multi-gateway WMNs. It is scalable as the mobility management role is dynamically shared among the gateways and among the MRs such that no single gateway or MR would become a bottleneck.

We developed an analytical model based on stochastic Petri net techniques to analyze the performance of LMMesh. We also performed a comparative study to compare LMMesh against a tunnel-based location management scheme, a pure routing-based scheme, and a pure pointer forwarding scheme. Our results demonstrated that LMMesh is consistently superior to these existing schemes for location management in WMNs. We attribute the superiority of LMMesh to the integration of routing-based location update and pointer forwarding.

To implement LMMesh on real mobile devices, the devices should have adequate computing power to perform the computational procedure presented in the paper. For mobile devices that are less powerful in computation, a table-lookup approach can be used to implement LMMesh without having to execute the computational procedure at runtime. Specifically, $K_{optimal}$

can be statically determined at the design time over a wide range of mobility and service characteristics and stored in a table for fast lookup. Then, during the execution of LMMesh, a simple table lookup can quickly determine $K_{optimal}$, based on the mobile user's service to mobility ratio as measured by the mobile user dynamically.

In the future, we plan to investigate how our proposed location management scheme can be extended to the case in which MCs may help with location information maintenance. We also plan to investigate if LMMesh can be tailored to benefit specific mobile applications such as multimedia multicasting to mobile groups in a WMN.

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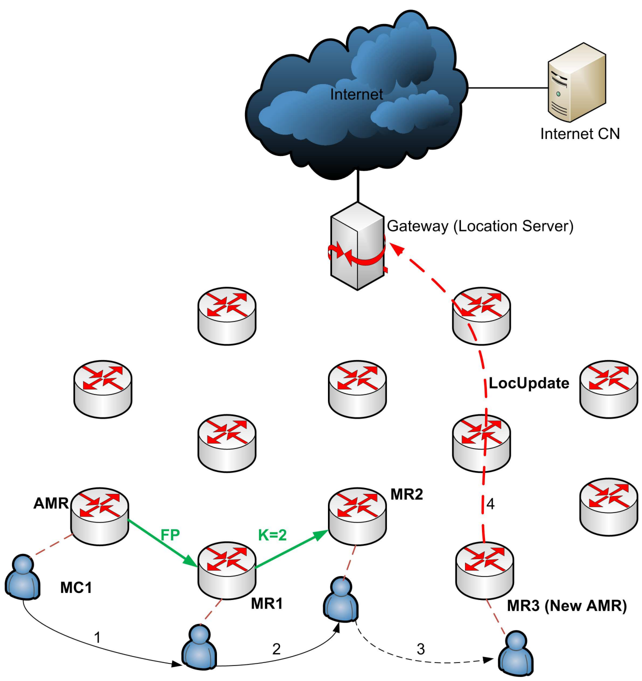

Fig. 1. The pointer forwarding method (*LocUpdate* means a location update message, and *FP* means a forwarding pointer).

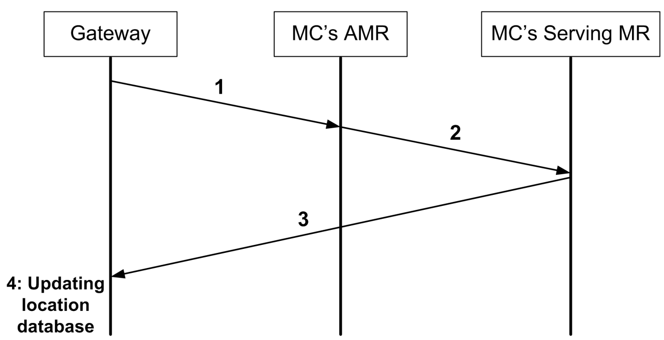

Fig. 2. The location search procedure for Internet sessions.

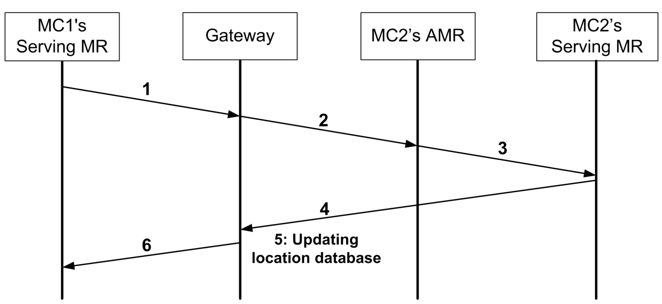

Fig. 3. The location search procedure for intranet sessions.

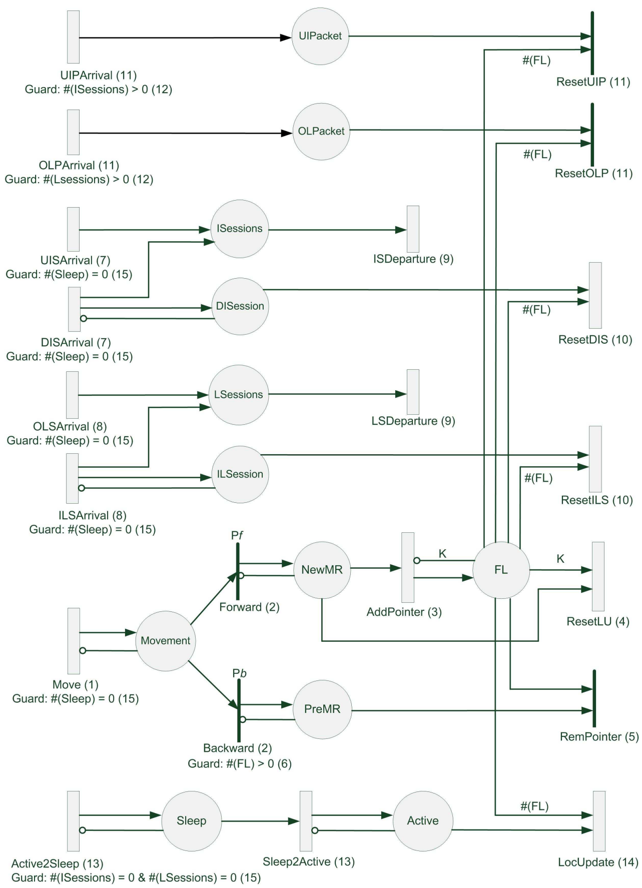

Fig. 4. The SPN model for LMMesh.

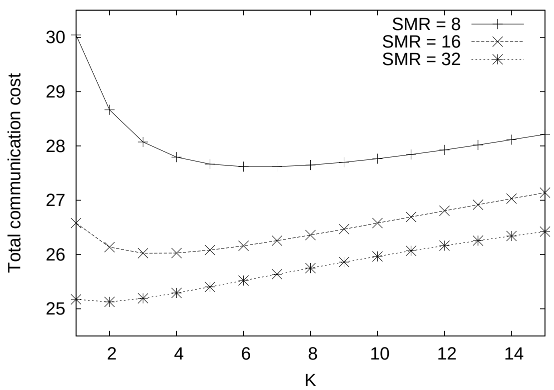

Fig. 5. Cost vs. K.

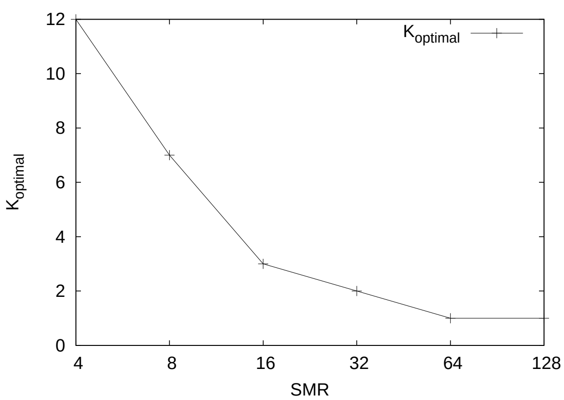

Fig. 6. $K_{optimal}$ vs. SMR.

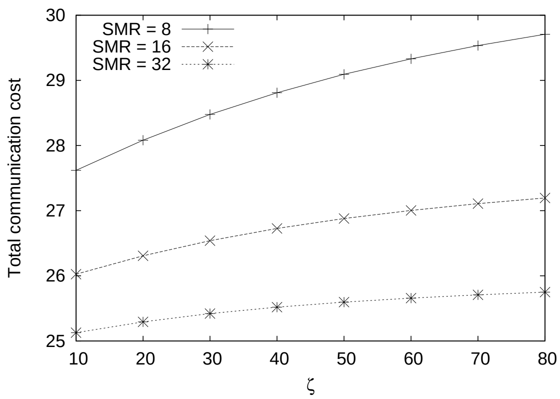

Fig. 7. Cost vs. ζ.

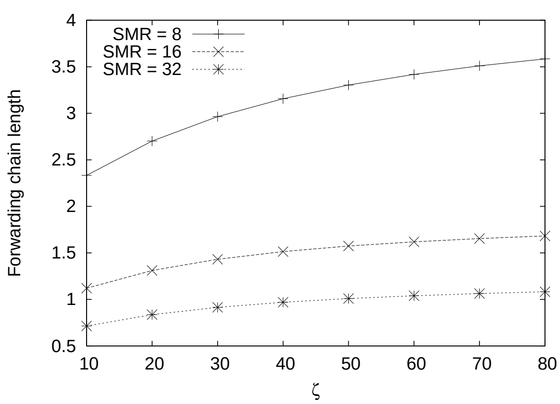

Fig. 8. Average forwarding chain length vs. ζ.

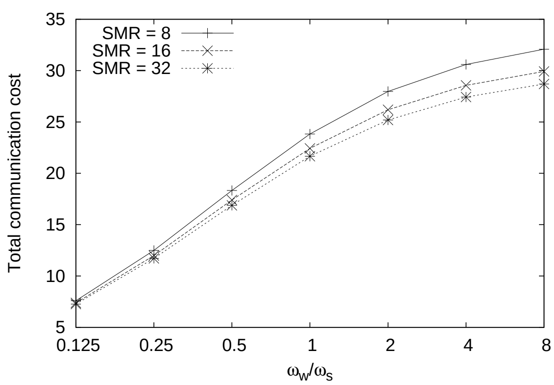

Fig. 9. Cost vs. ω_w/ω_s.

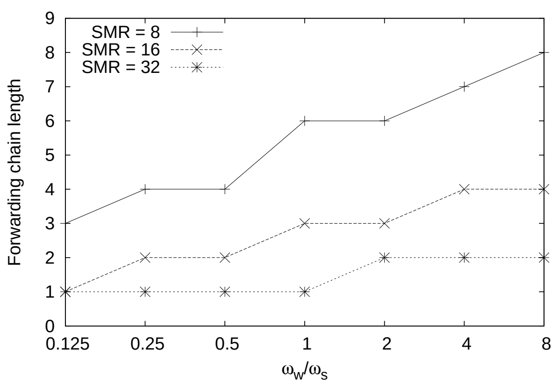

Fig. 10. $K_{optimal}$ vs. ω_w/ω_s.

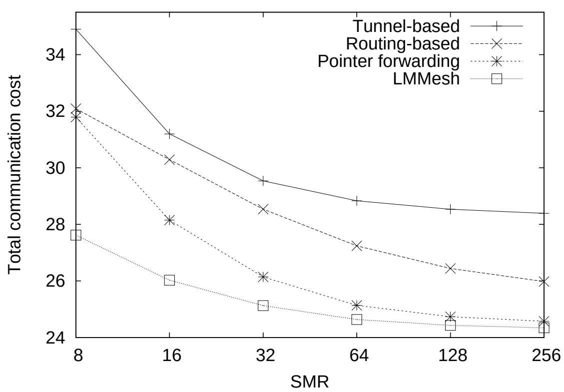

Fig. 11. Performance comparison: cost vs. SMR.

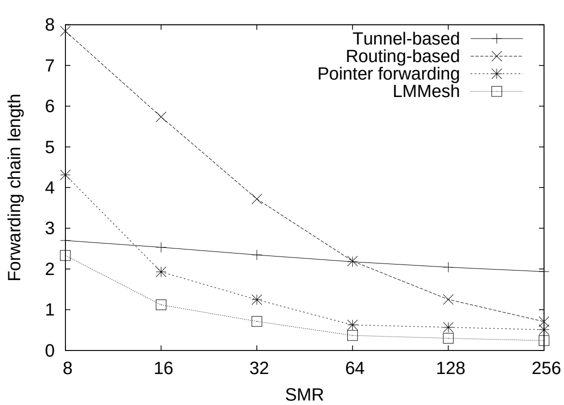

Fig. 12. Performance comparison: average forwarding chain length vs. SMR.

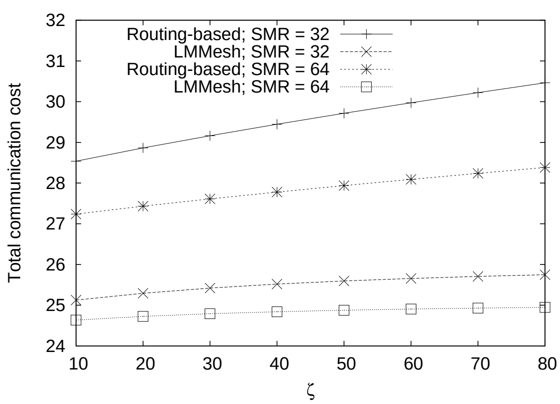

Fig. 13. Performance comparison: cost vs. ζ.

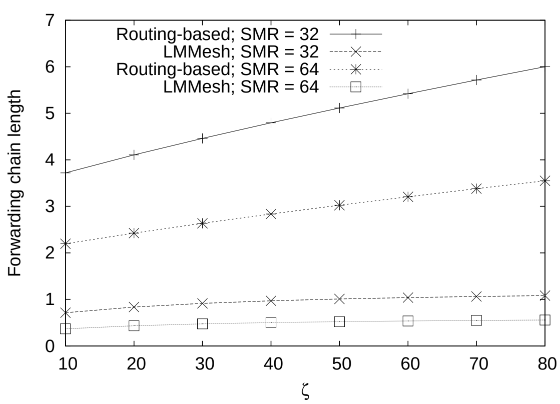

Fig. 14. Performance comparison: average forwarding chain length vs. ζ.

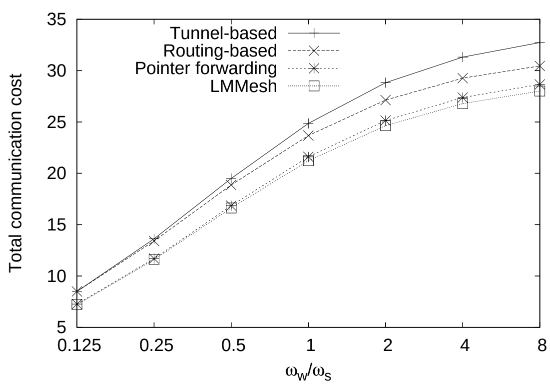

Fig. 15. Performance comparison: cost vs. ω_w/ω_s.

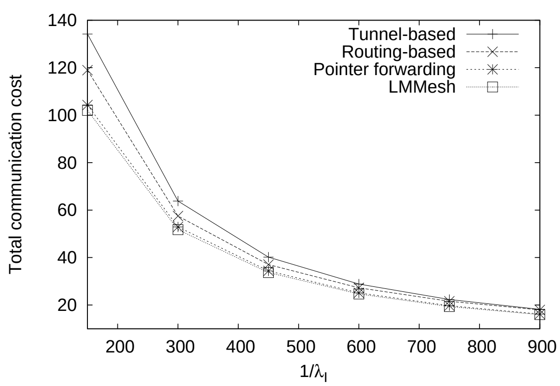

Fig. 16. Performance comparison: cost vs. λ_I.

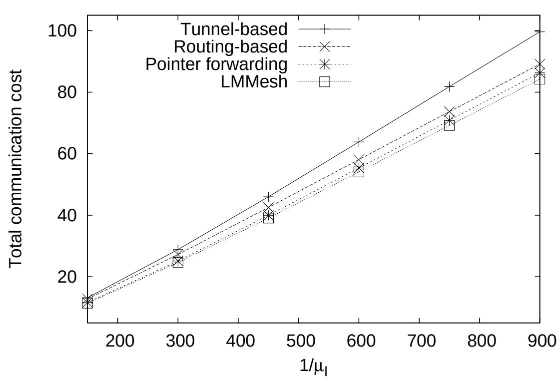

Fig. 17. Performance comparison: cost vs. μ_I.

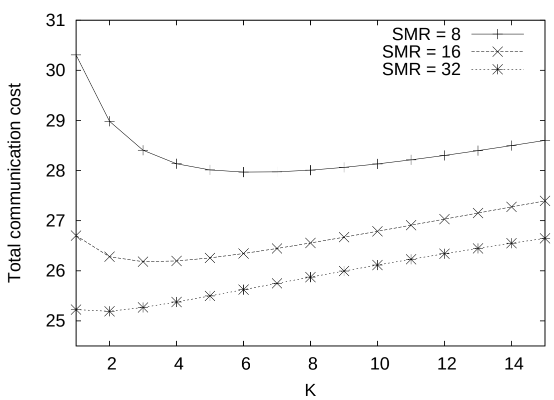

Fig. 18. Cost vs. K under the hexagonal network coverage model.

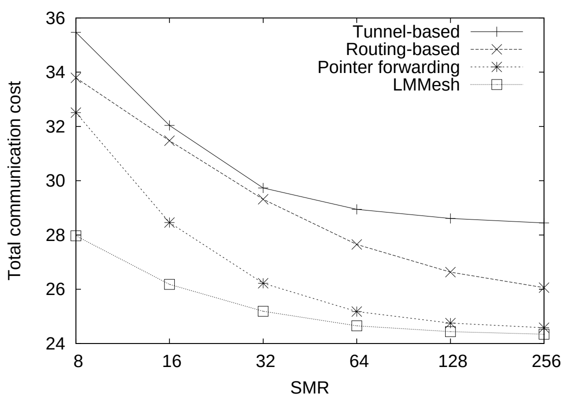

Fig. 19. Performance comparison: cost vs. SMR under the hexagonal network coverage model.