InterMR: Inter-MANET Routing in Heterogeneous MANETs

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Abstract—The advancements of diverse radio technologies and emerging applications have spawned increasing heterogeneity in mobile ad hoc networks (MANETs). But the collaborative nature of communications and operations often requires that these heterogeneous MANETs to be interoperable. Nonetheless, the existing interconnection protocols designed for the Internet (namely inter-domain routing protocol such as BGP) are not adequate for handling the unique challenges in MANETs. In this paper, we present a novel Inter-MANET Routing protocol called InterMR that can handle the heterogeneity and dynamics of MANETs. Our first contribution is an Inter-MANET address scheme based on a variety of node attributes (e.g., symbolic name, property, etc.); this allows dynamic merging/split of network topologies without a separate Name Server. Our second contribution is to provide a seamless routing mechanism across heterogeneous MANETs without modifying the internal routing mechanisms in each MANET. The proposed scheme can transparently adapt to topological changes due to node mobility in MANETs by dynamically assigning the gateway functionalities. We show, by packet-level simulation, that the performance of InterMR can be improved by up to 112% by adaptive gateway assignment functionalities. We also show that InterMR is scalable with only modest overhead by analysis.

I. INTRODUCTION

Mobile ad hoc networks (MANETs) are popular in dynamic environments where network infrastructure is not readily available or not adequate, such as in coalition military operations, emergency operations for disaster recovery, and vehicular communications (VANETs). In many situations, multiple ad hoc networks (belonging to different organizations or administrations) often need to communicate with each other so that they can share information, deliver commands/controls, and alert the other parties. For example, at the scene of a disaster, police, firefighters, and medical crews (each on a different MANET) may need to work together by sharing situation information (e.g. GIS info, building layout, traffic information) and coordinating rescue efforts with each other. Each group may use different wireless networking technologies, from physical layer (e.g. 2.4 GHz vs. 54 GHz) to routing layer (e.g. DSLR vs. AODV). This will represent a challenge even if the upper layers are compatible, featuring common applications running on top of standard protocols such as SIP, HTTP on TCP/IP. The focus of this paper is to enable interoperability across heterogeneous MANETs. We assume that PHY/MAC layer compatibility issues are resolved by placing suitable gateways across heterogeneous MANETs. Then the outstanding issues will be how to bridge these heterogeneous MANETs at network layer, considering the dynamic network topologies in MANETs and heterogeneous routing protocols within each MANET.

In the Internet, the Border Gateway Protocol (BGP) [21] is the de facto standard mechanism for the interconnection among *fixed* autonomous systems (AS). For MANETs, the inter-MANET routing design is faced with fundamentally different challenges compared to BGP, and surprisingly has not been adequately studied by the community as of yet. One of the major differences in MANETs is that the network topology changes dynamically – in the order of minutes or even seconds compared to hours/days in the Internet [17]. Also, in MANETs there are no clear boundaries between MANETs (i.e., multiple MANETs can overlap in the same geographic region) and

MANETs can arbitrary split/merge. Thus, the prefix based address scheme in BGP is not viable to properly aggregate IP addresses in a MANET [7].

In addition, at the technical level, drastically different routing protocols with different routing philosophies have extensively deployed in MANETs. For example, one MANET may run a reactive routing protocol whereas another MANET runs a proactive or geo-routing protocol. A viable inter-MANET routing solution must be able to bridge the gap between such diverse protocols and support interoperability among MANETs without requiring internal routing protocols to be changed.

The [7] paper was the first attempt to identify the challenges of inter-MANET routing and to provide a high level design of an inter-MANET routing framework. In this paper, we extend the previous work with the following major contributions:

1) We propose an attribute based address scheme that is transparent from split/merge operations of MANETs and at the same time does not require a separate name server.
2) We present detailed design of a practical Inter-MANET Routing protocol called InterMR to support interoperability across heterogeneous MANETs.
3) We present a novel distributed algorithm to dynamically elect active gateways so that we can maximize the inter-MANET connectivity when the network topology changes due to node mobility.
4) We fully implement InterMR in the ns-2 simulator and extensively evaluate its performance with different node mobility models. In general, we report that InterMR is effective in providing improved communication opportunities across MANETs. We also report that dynamic gateway election provides significant performance gain.
5) Finally we present analytical results on the control overhead caused by InterMR in comparison to the overhead of proactive and reactive routing protocols in each MANET.

The remainder of this paper is organized as follows. In Section II, we discuss the inadequacy of existing routing schemes to handle the interoperability problem. In Section III, we present the details of our protocol design and illustrate with examples. In Section IV, we present our simulation design and evaluation results. In Section V, we report on control overhead analysis, and finally, we conclude the paper in VI.

II. INSUFFICIENCY OF EXTANT ROUTING FRAMEWORKS

In this section, we review the extant routing protocols and approaches, and discuss why they are not suitable for inter-MANET routing.

	InterMR	BGP	Hybrid routings	Cluster routings
Support for Mobility	Yes	No	Yes	Yes
Support for Heterogeneity	Yes	Yes	Yes	No
Suppor for Autonomy	Yes	Yes	No	No

TABLE I
COMPARISON OF INTERMR WITH OTHER CANDIDATE SOLUTIONS

First, one may attempt to apply BGP or a simple variation of it directly to MANETs. This is a valid approach,

and when we designed InterMR, we borrowed some of the main design concepts from BGP such as intra- and inter-gateway protocol (a la i-BGP and e-BGP) and policy-based routing [7]. However, there are many design considerations for BGP that do not apply in the MANET scenarios and vice versa. First of all, one of the major issues that BGP has to handle is the large scale of the Internet. To handle a single AS with hundreds of thousands of hosts, BGP has been carefully augmented to handle the extreme scalability by adding mechanisms such as route reflection (a mechanism to hierarchically organize BGP routers in a single AS) and AS confederation (providing illusion of a single AS when actually multiple ASes are grouped together). On the other hand, in MANET environments, the scale of the mobile networks that must be interconnected is still a far cry from that of the wired Internet. Rather, the key challenges are the ever-changing network topology and the lack of physical MANET boundary due to node mobility and wireless characteristics. In addition, due to the challenges, the prefix-based address scheme in BGP is unsuitable for MANETs because it does not appropriately aggregate the IP addresses in MANETs which can be arbitrary partitioned and merged [7]. Instead, we propose an attribute based address scheme that adaptively defines the address of a MANET from all the attributes (e.g., symbolic names, properties, services, etc.) in the MANET, and the address is transparent from MANET split/merge. Thus, other than the basic BGP architecture, i.e., the concept of gateway that enforces routing policy by computing the path vector, and the concept of i-BGP/e-BGP components that separate intra/inter domain communications, we maintain that MANETs *deserve* their own inter-MANET routing design.

One of the main challenges for interoperability in MANETs is to support heterogeneous intra-MANET routing protocols. In the literature, there have been several proposals to enable communication among heterogeneous routing protocols albeit for different purpose. For example, SHARP [20] uses both proactive and reactive routing protocols to adapt different traffic patterns and improve performance. The basic idea of SHARP is to create proactive routing zones around the nodes with lots of data traffic, and use reactive routing in other areas. Although the hybrid routing protocols enable communication between proactive and reactive routing protocols, they require nodes to be controlled by the same administrative policies and do not support autonomous operations by *multiple* MANETs. Thus they do not provide a systematic solution to interoperability among multiple MANETs with different routing protocols.

Structurally speaking, inter-MANET routing has some similarity with cluster-based routing and hierarchical routing in MANETs [8]. The main goal of the latter is to provide a scalable routing solution in a *single* MANET. Basically these protocols create small clusters from a single MANET, select a head for each cluster, and then form a routing backbone among the cluster heads to achieve better scalability. While one may think this inter-cluster communication looks similar to inter-MANET routing problem at hand, it should be clear that we cannot use a cluster-based routing protocol for inter-MANET routing because there is no single master that can run a cluster routing protocol over multiple heterogeneous MANETs. In other words, cluster-based routing and hierarchical routing protocols operate in a *homogeneous* environments, where nodes share the same set of policy and routing protocol. On the other hand, the goal of inter-MANET routing should be to enable interoperations of *heterogeneous* MANETs with autonomous control, where each MANET is allowed to use different routing protocols and routing policies.

In the literature, there have been several proposals for enabling inter-MANET communication among heterogeneous wireless networks [6], [10], [11], [15], [22]. Plutarch [10] is an architecture that translates address spaces and transports protocols among MANETs to support interoperation of heterogeneous networks, and TurfNet [22] is a proposal for inter-MANET networking without requiring global network addressing or a common network protocol. However, these are very high level architectures providing only sketches of the required components (e.g., translation of different naming spaces, and different protocols). The authors of [15] compare different inter-MANET routing choices based on a strong assumption that all nodes act as gateway nodes. Dressler et al. propose a distributed hash table (DHT) based inter-MANET routing in ad hoc networks by surrendering the control of underlying routing protocols of MANETs [11]. Chandrashekar et al. design a domain based hierarchical routing in MANETs [6]. However their schemes do not have the concept of dynamic gateway election to adapt to network topology changes, and their goal is not to maximize the inter-MANET connectivity.

In summary, while prior works have considered a number of important issues regarding MANET interoperation, none has provided a workable solution in heterogeneous MANET scenarios. Our work is founded on solid principles, but also attempts to provide a practical solution to the inter-MANET routing problem for dynamic MANET environments. Table I compares InterMR to existing routing protocols based on three fundamental metrics- mobility, heterogeneity and autonomy.

III. PROTOCOL DESIGN

A. Preliminaries

In this section, we first provide the basic definitions and assumptions for our protocol design. We define a MANET as a logical grouping of mobile nodes, where all the nodes in the same MANET employ the same wireless PHY/MAC and routing protocols and are governed by a single administrative entity. We assume that only the nodes in the same MANET can directly communicate with each other without the support of InterMR; direct communication between nodes in different MANETs may not be allowed due to policy constraints (e.g., security and access control policies) not just because of difference in network technologies. Therefore, the communication across MANETs must go through a set of special nodes called *gateways*. In other words, a node in MANET A can communicate with another node in a neighboring MANET B by first sending a packet to a gateway in MANET A, which then passes the packet to a nearby gateway in MANET B and then finally the packet is delivered to the destination.

To support inter-MANET communication in dynamic MANET environment, we design the protocol to perform the following main operations:

1. Intra-MANET Topology Change Detection: As discussed earlier, one of the key characteristics of a MANET is dynamic network topology, and thus we need to handle this issue when designing an inter-MANET routing protocol. There are two types of topology changes. First, nodes belonging to a single MANET can become partitioned into multiple sub-MANETs due to node mobility. Such a topology change must be detected by gateways in each sub-MANET. If the underlying routing protocol of the MANET is proactive, the partition will be detected automatically by the underlying routing protocol (via periodic route updating). However, if a partition happens in a reactive MANET, the event may not be detected for a while until a new message needs to be sent to a destination in a disconnected partition. To support change detection within a single MANET, we define a sub-protocol called *i-InterMR*, by which gateways maintain soft state of MANET topology via periodic beacons. Failure to receive a beacon indicates a partition. It should be noted that this probing only detects partitions involving active gateways.

2. Inter-MANET Topology Change Detection: The second type of the topology change is the MANET-level topology change. For instance, the neighboring MANETs of MANET A may change from MANET B, C, D to D, E due to node movement. As MANETs dynamically move, gateways in each MANET are required to detect new neighboring MANETs

and start exchanging routing information with them and retire old inter-MANET routing entries. To handle this, we design another sub-protocol called *e-InterMR* which is used to maintain and discover inter-MANET topology changes via inter-MANET beacons and propagation of inter-MANET routing information (e.g., routing entries of destinations in other MANETs). For this we require gateways to maintain direct connectivity with adjacent gateways of other MANETs. We note that the beacon periods of both i-InterMR and e-InterMR can be adaptively determined based on the dynamicity of topology changes. We will not pursue adaptive beaconing in this paper as it is a well known issue and a rather small extension to the main design.

3. Dynamic Gateway Election: [7] considered a simple case where some nodes are initially pre-designated as gateways whose movement is determined by their mission objectives not by infrastructure goals such as constructing an inter-MANET backbone. However, it is not difficult to understand that, in some cases, such an approach will result in sub-optimal performance in terms of inter-MANET connectivity. For example, when a single MANET is partitioned into multiple sub-MANETs, it is possible that some of them may not have any gateways to connect to the rest of the MANETs. There are various ways to tackle this issue, e.g., by controlling the mobility of gateways, or by electing gateway nodes dynamically in response to topology change. In this paper, we take the latter approach since we feel mobile nodes are now powerful enough to perform multi-protocol translation and extra inter-MANET operation. However, making all nodes to become gateways is not a good design either because: (a) it will quickly deplete the scarce battery power even when the node is not participating in inter-MANET communications, and (b) it will generate excessive control messages between any node to any other nodes in the entire network. In this paper, we take a practical approach assuming that there are a set of nodes in each MANET that can become gateways when needed. We call them potential (or candidate) gateways and when they become actively involved in InterMR operation, we call them *active gateways*. When gateways are active, they maintain the inter-MANET routing information, perform protocol translation and policy-based data forwarding as necessary.

4. Attribute based Addressing and Inter-MANET Routing: In InterMR, we define the address of a MANET to be the Bloom Filter (BF) [2] of all the attributes pertaining to the MANET, most prominently (but not exclusively) the symbolic host names. The Bloom Filter is the OR of the hashes of the attributes based on a universally known function. An attribute is said to be in the Filter if the Filter matches all the *ones* of the attribute hash. This address choice guarantees the uniqueness of the address since attributes are different from MANET to MANET. Moreover, the BF functions as Name Server for the interconnected MANET system. If a gateway has the full set of MANET addresses (i.e. the corresponding BFs), it finds which MANET a given destination is by matching its attribute hash across BFs. The BF can also be used to store MANET wide characteristics. For example, there is an ambulance or a doctor in this MANET (important in search and rescue operations), or there are non authenticated nodes in this MANET (important in privacy or security sensitive routing). Thus, the attribute based address scheme is a major departure from IP type address schemes and it is transparent from MANET split/merge operations that the IP based address schemes cannot support well. One caveat about BF is false positives. Namely, when checking an attribute in the BF tables, more than one destination MANET address is returned. Since the false positive probability can be easily kept below 5%, say, by proper sizing of the BF field (80bytes used in InterMR with three hash functions to support 100 nodes [3]), the penalty is the extra overhead to route to two destination when this unlikely event happens. It should be noted that there are several DHT based MANET routing protocols that provide attribute

Control Message	Description
Beacon	Periodically sent by (1) e-InterMR for detection of new external MANETs and (2) i-InterMR for detection of intra-MANET topology changes
Routing Table Request	Sent by both e-InterMR and i-InterMR to exchange InterMR routing tables when new gateways are discovered
Routing Table Reply	Reply message to *Routing Table Request*
Routing Table Update	Sent by both e-InterMR and i-InterMR to incrementally exchange routing table updates

TABLE II
INTERMR CONTROL MESSAGE

routing, and thus, like InterMR combining routing and Name Server functions [1], [5], [24]. However, these DHT based routing schemes have been so far *limited* to single MANETs. They cannot be extended to a *collection* of multiple MANETs, where each MANET can independently split/merge, etc. In InterMR, the BF is computed by each active gateway in a MANET as it monitors MANET membership. It will be noted that the MANET address changes dynamically as the MANET splits/merges and as it acquires/loses members of the MANET.

For inter-MANET route information, each active gateway keeps a *Distance Vector* of next gateways to each MANET destination. The distance vector information is proactively propagated with Fisheye principles [18]. The propagation rate decreases as the updates are moving away from the origin. This has an implication on address validity. For instance, an active gateway may have a blurred view of addresses of distant destinations. Nevertheless, proper routing to the desired attributes is preserved since the packet is routed in the *generally correct* direction. This direction becomes more and more accurate as the packet approaches destination. This principle was already proven for Fisheye Routing. It follows from the fact that routing updates, albeit slowed down by Fisheye propagation, travel much faster than physical nodes. If the entire path to destination is of interest (for instance, to verifying the *security* of the path), one can use the *Path Vector* scheme adopted by BGP. In order to minimize overhead induced by the path vector, a gateway can use the path construction scheme proposed in [25]. The Distance Vector includes: destination, hop distance and predecessor gateway to the destination on the minimum hop path (gateway level). The source can then reconstruct the path from its own routing table by working recursively from destination to source. Finally, if there is any need for protocol translation between two MANETs, gateways can perform such transformation of protocol functions and packet format (i.e., protocol gateway functionality). The details of the inter-MANET routing is described in Section III-B1.

B. Illustration of Inter-MANET Routing

We first explain the inter-MANET routing operation of InterMR with an illustrative example followed by the detailed descriptions of InterMR design.
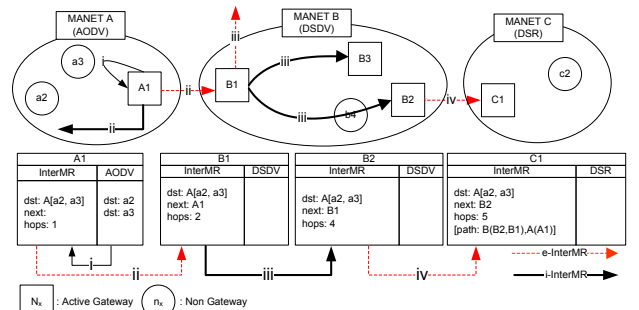

Fig. 1.   Propagation of routing information

Notation	Description
i	Node i
$BFH(i)$	MANET ID of i
$M(i)$	A set of intra-MANET members in BFH(i)
$G^{\text{intra}}(i)$	A set of intra-MANET gateways(inactive and active) in BFH(i)
$G_A^{\text{intra}}(i)$	A set of active gateways in BFH(i)
$G_A^{\text{inter}}(i)$	A set of active gateways in other MANETs within one hop distance of i
P_{GW}	Tunable parameter, where $P_{\text{GW}} = \frac{|G_A^{\text{intra}}(i)|}{|G^{\text{intra}}(i)|}$

TABLE III
NOTATIONS

1) Illustrative Example: Figure 1 presents a simple route propagation procedure and Table II describes four types of control messages of InterMR. In this example, new route entries of nodes, $a2, a3$ in MANET A, are propagated across three heterogeneous MANETs. The figure illustrates each step of the route propagation procedure and changes in the routing tables of each active gateway. The steps to propagate the new route entries across the multiple MANETs are (see Table III for notations):

(i) $A1$ discovers the non-gateway nodes, $a2, a3$, by its underlying routing protocol, AODV. Based on the MANET membership, $A1$ generates a new address of the MANET using a bloom filter hash function (BFH), and here we denote it as A for simplicity. Then $A1$ records $a2, a3$ entries in the InterMR routing table.

(ii) $A1$ sends a *Routing Table Update* message to $G_A^{\text{inter}}(A1)$, $G_A^{\text{intra}}(A1)$ by e-InterMR and i-InterMR respectively.

(iii) $B1$ receives the new route entries from $A1$ and updates its InterMR routing table. Then it sends out a *Routing Table Update* message to $G_A^{\text{inter}}(B1)$ and $G_A^{\text{intra}}(B1)$.

(vi) $B2$ receives the new route entries from $B1$ and updates its InterMR routing table. Then $B2$ sends out a *Routing Table Update* message to $G_A^{\text{inter}}(B2)$. However, it does not send an update message to $G_A^{\text{intra}}(B2)$ since the update came via i-InterMR. $C1$ receives the new entries from $B2$, and records the information into its InterMR routing table.

(v) If $C1$ wants to ensure security of the path, the exact path vector (gateway level) to the destination will be recursively computed by following next hop gateways.

As shown in Figure 1, InterMR allows gateways to build path-vectors for each route entry when needed. Based on the path vector, each gateway can apply its MANET policy. For example, if the MANET policy of C indicates that MANET B is untrustworthy, gateway $C1$ does not forward any packets to $a2, a3$ as the path must travel through B. $C1$ may also exclude the entries in advance. This example represents that InterMR supports *opaque* interoperations by (1) allowing each MANET to have its own control of intra-MANET routing, and (2) allowing each MANET to have its own inter-MANET routing policies, similar to BGP.

Pseudocode 1 Periodic inter-MANET routines

1: broadcast e-InterMR *Beacon*
2: remove expired route entries
3: update InterMR routing table based on the native ad-hoc routing table
4: **if** (InterMR routing table changed) **then**
5:　send *Routing table Update* to $G_A^{\text{inter}}(i)$ and $G_A^{\text{intra}}(i)$
6: **end if**

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2) e-InterMR: Pseudocode 1 is executed periodically to 1) broadcast e-InterMR *Beacons*, 2) remove expired route entries in InterMR routing table, 3) read underlying ad-hoc routing table and update $M(i)$ and InterMR routing table, and 4) send *Routing table Update* to $G_A^{\text{inter}}(i)$ and $G_A^{\text{intra}}(i)$ when InterMR

routing table changes. The changes happen when a new route is discovered or an existing route is updated/expired. Note that $M(i)$ is provided by the underlying routing protocol of active gateways.

Pseudocode 2 Main inter-MANET routine

1: update $G_A^{\text{inter}}(i)$ and InterMR routing table when receiving *Beacon* according to inter-MANET policy
2: update InterMR routing table when receiving *Routing table Update* according to inter-MANET policy
3: **if** (InterMR routing table changed) **then**
4:　send *Routing table Update* to $G_A^{\text{inter}}(i)$ and $G_A^{\text{intra}}(i)$
5: **end if**
6: **if** (recv data packet) **then**
7:　handleDataPacket(pkt)
8: **end if**

Pseudocode 2 is the core routine of e-InterMR. An active gateway i receives an e-InterMR *Beacon*. If a new active inter-MANET gateway is detected by the beacon, it adds the new gateway to $G_A^{\text{inter}}(i)$ based on its MANET policy and exchanges its InterMR routing table with the new gateway. If the beacon is from an existing gateway, it updates $G_A^{\text{inter}}(i)$. The active gateway also receives an e-InterMR *Routing Table Update* and it updates its InterMR routing table based on its MANET policy. If the InterMR routing table changes, a *Routing Table Update* is sent to $G_A^{\text{inter}}(i)$ and $G_A^{\text{intra}}(i)$. Finally, when the active gateway receives data packets, it passes the data to function HandleDataPacket(), which is described in Pseudocode 3.

Pseudocode 3 Function HandleDataPacket(pkt)

1: **if** (destination is listed in native ad-hoc routing table) **then**
2:　forward the packet by using native ad-hoc routing
3: **else if** (destination is listed in InterMR routing table) **then**
4:　forward the packet by using InterMR according to inter-MANET policy
5: **else**
6:　drop the packet
7: **end if**

The function, HandleDataPacket(), handles data packets when an active gateway receives data packets. It is used by both e-InterMR and i-InterMR. When the gateway receives a data packet, it first checks if the destination appears in the native ad-hoc routing table. If it does, the gateway forwards the packet based on its native routing protocol. If the destination is shown in the InterMR routing table instead of the native ad-hoc routing table, the gateway forwards the data packet to the next hop gateway. The gateway drops the data packet if the destination address is not shown in either of the routing tables.

Pseudocode 4 Main intra-MANET rountine

1: send i-InterMR *Beacon* to $G^{\text{intra}}(i)$
2: //a new active gateway detected or an existing active gateway expired
3: **if** ($G_A^{\text{intra}}(i)$ changed) **then**
4:　generating a new MANET address, BFH(i)
5:　invoking e-InterMR to send *Routing Table Update* (in Pseudocode 2)
6: **end if**
7: **if** (receive *Routing Table Update* from i-InterMR) **then**
8:　update InterMR routing table accordingly
9:　**if** (InterMR routing table changed) **then**
10:　　send *Routing Table Update* to $G_A^{\text{inter}}(i)$
11:　**end if**
12: **end if**
13: **if** (recv data packet) **then**
14:　handleDataPacket(pkt)
15: **end if**

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3) i-InterMR: Pseudocode 4 is the main routine of i-InterMR. The main functionalities of the routines are to: (1) periodically send *Beacon* to $G^{\text{intra}}(i)$, (2) maintain $G_A^{\text{intra}}(i)$, and (3) exchange route update among $G_A^{\text{intra}}(i)$. The purpose

of i-InterMR beacon is to maintain $G_{\mathsf{A}}^{\mathsf{intra}}(i)$. When topology is changed, the active gateway i generates a new MANET address and other gateways in $G_{\mathsf{A}}^{\mathsf{intra}}(i)$ also generate an identical MANET address with i in a fully distributed manner by using a bloom filter hash function(BFH) provided by one of MANET policies. The hash function considers various attributes in the MANETs (e.g., symbolic names of MANET members, MANET property, etc.) which are unique from MANET to MANET. Once the new MANET address is generated, the active gateway sends a *Routing Table Update* to $G_{\mathsf{A}}^{\mathsf{inter}}(i)$. When the active gateway receives a *Routing Table Update* from $G_{\mathsf{A}}^{\mathsf{intra}}(i)$, it updates the InterMR routing table and propagates the updates to $G_{\mathsf{A}}^{\mathsf{inter}}(i)$. However, the active gateway does not initiate further updates to $G_{\mathsf{A}}^{\mathsf{intra}}(i)$ because other active gateways in $G_{\mathsf{A}}^{\mathsf{intra}}(i)$ also receive the *Routing Table Update* from the originator of the update in the same partition.

C. Dynamic Gateway Election

In this section, we present a novel distributed gateway election mechanism, by which potential gateways in each partition can determine whether they should become active gateways or not to maximize inter-MANET connectivity while satisfying the constraints on the number of active gateways after the topology has been changed. There are three major steps in the election mechanism: (1) collecting of connectivity information, (2) detecting intra-MANET topology changes, (3) making local decision whether or not to become active gateways.

1) Illustrative Example: Figure 2 presents an example of the dynamic gateway election procedure. Initially G2 and G4 are active gateways. We assume that the constraint on the maximum number of active gateways in a partition is 50%. We assume the ratio is determined by a MANET policy. If a MANET wants better reachability and connectivity, it will use a higher rate. If a MANET is more concerned about control overhead, then it will activate only small fraction out of candidate gateways.

(i) Active gateways broadcast e-InterMR beacons, while both active/inactive gateways exchange i-InterMR beacons. Both beacons contain reachable destination information. In the figure, G1, G2 and G3 can overhear e-InterMR beacons from other partitions, but G4 only receives i-InterMR beacons from G1, G2, and G3.

(ii) Assume that the connectivity information at each nodes is (G1:21),(G2:22),(G3:23),(G4:9), where (x,y) represents (node id, the number of distinct reachable destinations). By exchanging i-InterMR beacons, each of them locally identifies the connectivity information of others. Based on the MANET policy, they elect the top 2 gateways (50% among 4 gateways) with the most number of reachable destinations as active gateways. In the steady state, ideally, the connectivity information of all gateways is consistent and all gateways determine G2 and G3 as active gateways. However, in practice, when the gateways exchange i-InterMR beacons, some of them can be lost due to wireless errors/fading and transition node movement, etc. In such a case, some of them may reach incorrect conclusions, and as a result more or less number of gateways may be elected temporarily.

(iii) If each gateway knows that only 50% of candidate gateways should be active, temporary inconsistency will be corrected eventually. For example, consider a case when G1 did not receive a beacon from G2 and incorrectly activate itself as a gateway. In this case, if G3 receives an i-InterMR control message from G1, Then G3 sends an i-InterMR control message to G1 suggesting that it should not be active. Alternatively G1 may discover that G2 is a better connected node when it finally receives a beacon
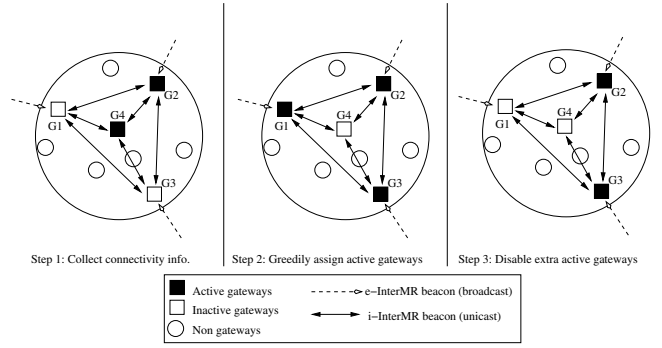

Fig. 2. Dynamic gateway election procedure

from G2. In either case, G1 will eventually discover that it should not be active.

In the baseline design, we use reachablilty as the main metric for the dynamic gateway election since it can be easily obtained at the routing layer. However, we think that incorporating other inter-MANET metrics is not difficult if we can collect them from different layers, such as the wireless link quality (PHY-layer), traffic pattern (APP-layer), energy consumption, etc.

Pseudocode 5 Collect connectivity information(pkt)

1: SRC = message's source address
2: **if** (recv. e-InterMR Beacon or recv. i-InterMR Beacon) **then**
3:     update the reachable destinations and expiration time of SRC
4: **end if**

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2) Specification of Dynamic Gateway Election:
Step 1: Collecting connectivity information:

Pseudocode 5 describes how each gateway collects connectivity information. Active gateways periodically broadcast (using e-InterMR beacons) their connectivity in terms of list of distinct reachable destinations. A gateway i (either active or inactive) overhears the beacon from other MANETs and updates its reachable destination list. The gateway sends an i-InterMR beacon to $G^{\mathsf{intra}}(i)$ with the list of reachable destinations collected from e-InterMR beacon and from its native routing protocol.

Pseudocode 6 Periodic detection of intra-MANET topology changes and greedy active gateways election

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1: INPUT : $G^{\mathsf{intra}}(i)$
2: //a new gateway detected or an existing gateway expired
3: **if** ($G^{\mathsf{intra}}(i)$ changed) **then**
4:     sort($G^{\mathsf{intra}}(i)$);
5:     $G_{\mathsf{A}}^{\mathsf{intra}}(i)$ = top P_{GW} of gateways from $G^{\mathsf{intra}}(i)$
6:     **if** ($i \in G_{\mathsf{A}}^{\mathsf{intra}}(i)$) **then**
7:         status = active
8:     **else**
9:         status = inactive
10:     **end if**
11: **end if**

Step 2: Detecting topology changes and dynamic gateway election:

After collecting connectivity information of $G^{\mathsf{intra}}(i)$ in the partition, the gateway, i, periodically inspects topology changes in its partition (i.e., a new gateway joins, an existing gateway leaves). If a change is detected, a new gateway election is performed. The gateway ranks $G^{\mathsf{intra}}(i)$ based on "connectivity metric" (i.e., number of destinations) that each $G^{\mathsf{intra}}(i)$ can reach over the network. Then the gateway elects top P_{GW} of $G^{\mathsf{intra}}(i)$ as active gateway and maintains $G_{\mathsf{A}}^{\mathsf{intra}}(i)$.

The gateway then scans the list of adjacent MANETs and makes sure that at least one gateway per adjacent MANET is in the active set, regardless of its rank, to maintain connectivity. Note that this election also reflects the size of each partition (ie, number of elected nodes is proportional to size). If we elect a fixed number of active gateways in every partition, the active gateways might be either under-elected or over-elected. After the gateway updates $G_A^{intra}(i)$, it checks whether its node id, i, is in $G_A^{intra}(i)$. If it is, the gateway sets its status as active gateway. Otherwise it sets the status as inactive gateway.

Pseudocode 7 Disabling extra active gateways

1: **if** (recv. i-InterMR control message) **then**
2:     SRC = control message's source address
3:     add SRC to $G_A^{intra}(i)$
4:     detect extra active gateways from sort($G_A^{intra}(i)$)
5:     send disable control message to those extra active gateways
6:     remove extra active gateways from $G_A^{intra}(i)$
7: **end if**

Step 3: Ensuring faster convergence: Due to the characteristics of MANET, there may be instances when every gateway in a partition does not have the identical view of the network. In this case, some MANET might over-elect or under-elect active gateways. Thus when gateways in a MANET detect unnecessary active gateways, they should notify unnecessary gateways so that they can deactivate themselves. To achieve this, when active gateways exchange control messages, they check the source address (SRC) of the control messages with their $G_A^{intra}(i)$. If SRC is not in $G_A^{intra}(i)$, it means an extra gateway is elected. The active gateways rank $G_A^{intra}(i)$ including SRC based on the connectivity information and send out control messages to the extra gateways. Similar steps will be taken to handle too small number of active gateways.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of InterMR in a packet-level simulation environment with various simulation parameters such as different ratio of active gateways, and mobility models. In addition, we compare the performance of InterMR with static and dynamic gateway assignment schemes. In the static scheme, we randomly preconfigure a set of nodes as active gateways. In the dynamic scheme active gateways are elected *on-the-fly* according to the gateway election algorithm described in Section III-C. We compare the performance of these two gateway assignment schemes with two baseline cases. In the first baseline case, we do not deploy any gateways. There exist D heterogeneous MANETs (where D is the number of MANETs, with n nodes each) but they cannot communicate with each other since no gateways are available. This case is called *'w/o InterMR'* and represents the case without inter-MANET routing. The second baseline case is an upper bound on the performance: namely, we assume all nodes are in a single proactive routing MANET, with the total number of nodes is $D \times n$. This case achieves the maximum performance since it guarantees shortest paths between all source-destination pairs (which will be strictly better than what can be achieved with optimal gateway placement).

A. Simulation Setup

We implemented InterMR in NS-2.32 [16]. Gateways are equipped with two wireless network interfaces. Each interface is separately utilized for inter-MANET and intra-MANET communications with distinct wireless channels. However, in order to fairly compare the performance of InterMR with the baseline cases, we assign the same channel for all of communications. We use IEEE 802.11b with communication range $250m$.

The followings are simulation setup for Section IV-C and IV-C. InterMR is evaluated with two different mobility

models: Random Waypoint Mobility Model (RWP) and Reference Point Group Mobility (RPGM) [13]. We set the mean of node speed as $2m$/s. We deploy 50 nodes in $1500 \times 1500m^2$ area and they are evenly divided into two heterogeneous MANETs except for the single proactive MANET case. In the single MANET case, we only have one MANET with 50 nodes. For intra-MANET routing, we use a proactive routing protocol (DSDV). Except the single MANET case, we configured so that nodes in different MANET cannot directly communicate each other. Out of possible source-destination pairs, we consider four 1Mbps CBR flows over UDP: two of them are *inter-MANET flows* where the source and destination of each flow belong to different MANETs. The other two flows are *intra-MANET flows*, i.e., source and destination are in the same MANET. We conduct each simulation for 1500 simulation seconds. The results are averaged from 20 runs and presented with 95% confidential interval.
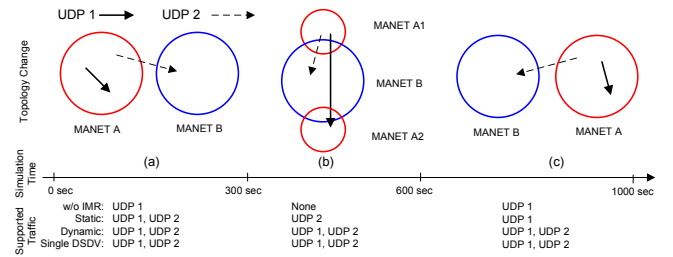
B. Scenario 1: InterMR with a simple Group Mobility

Fig. 3.   Relative position of MANET A and B at (a) Initial, (b) MANET A is partitioned, and (c) MANET $A1$ and $A2$ are merged.
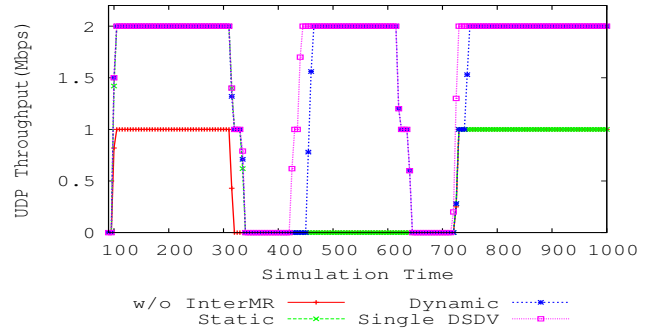

Fig. 4.   UDP Throughput(Mbps) with different schemes

	w/o InterMR	Static	Dynamic	Single DSDV
UDP Throughput(Mbps)	0.49	0.72	1.33	1.41

TABLE IV

In this section, we validate the operations of InterMR with a simple pre-defined group mobility. The goal of this scenario is to demonstrate how InterMR adjusts to network topology changes and recovers from gateway failure. As shown in Figure 3, we have two heterogeneous MANETs (A and B) and deploy four nods per MANET. At simulations time 300 second, MANET A moves from left to right passing by MANET B, and it becomes partitioned into two sub-MANETs (MANET A1, A2). At time 600 second, the sub-MANETs start to move and become merged. We generate two 1Mbps CBR flows starting at 100 second: initially one is an intra-MANET flow (UDP 1) within MANET A and the other is an inter-MANET flow (UDP 2) from MANET A to MANET B. While MANET A is partitioned, UDP 1 becomes inter-MANET flow as the source and destination of the flow are
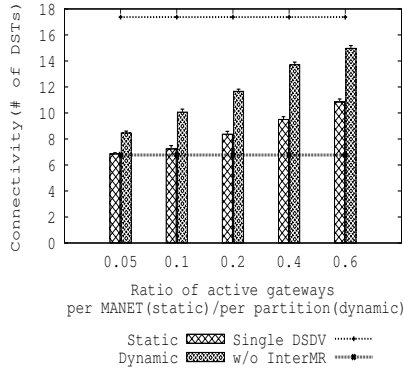
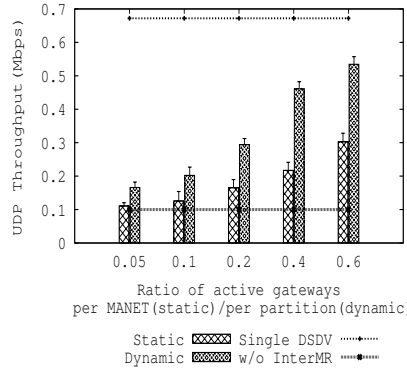Fig. 5.   Connectivity w/ RWP

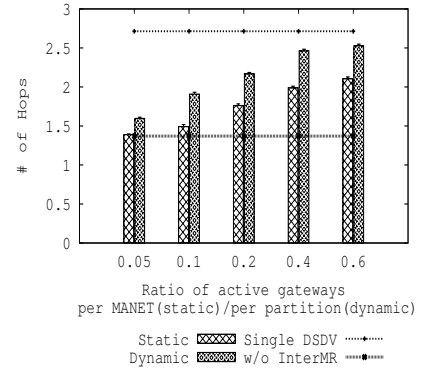Fig. 6.   Aggregated UDP throughput w/ RWP

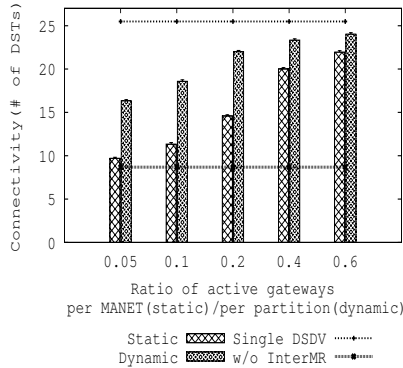Fig. 7.   Average Number of Hops w/ RWP
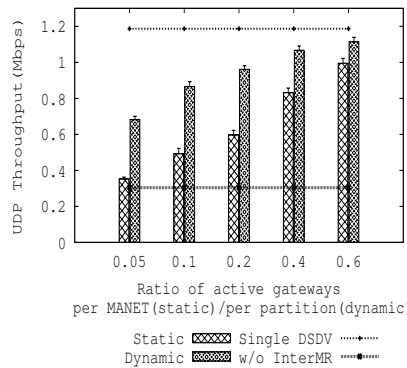

Fig. 8.   Connectivity w/ RPGM

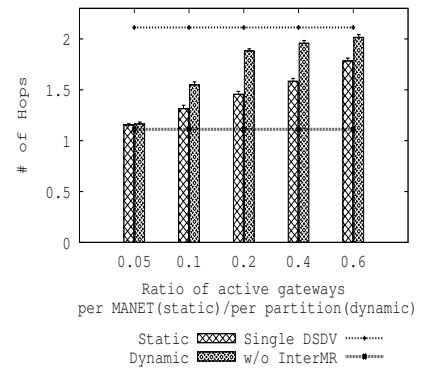Fig. 9.   Aggregated UDP throughput w/ RPGM

Fig. 10.   Average Number of Hops w/ RPGM

not in the same MANET. We evaluate InterMR with static and dynamic schemes and also provide two guideline cases ('w/o InterMR' and Single DSDV); all of nodes in Single DSDV case belong to one MANET and they are all connected via multi-hop communication. While we pre-assign one active gateway in each MANET with static scheme, we dynamically elect one active gateway per MANET with dynamic scheme. Depending on the availability of active gateways in MANETs, data packets on the UDP flows can be either delivered or dropped with different schemes.

(a): On the initial topology, UDP 1 is supported by all of schemes as the source and destination are positioned in the same MANET. On the other hand, 'w/o InterMR' cannot support UDP 2 because it is an inter-MANET data traffic.

(b): MANET A is partitioned into MANET A1 and A2, and the source and destination of UDP 1 are located in MANET A1 and A2 respectively. 'w/o InterMR' cannot support both UDP flows because all of flows become inter-MANET traffic. In static case, the pre-assigned active gateway belongs to MANET A1 and MANET A2 does not have any active gateways. Thus the scheme only supports UDP 2 from MANET A1 to B. However, dynamic scheme *adaptively* elects a new active gateway in MANET A2 and recovers *both* UDP flows by the proposed dynamic gateway election and inter-MANET routing operations of InterMR. Note that dynamic scheme shows a little delay for the recovery compared to Single DSDV case. It is because InterMR does the election and route information exchanges across multiple MANETs, whereas Single DSDV case simply discovers new node by beacons.

(c): MANET A1 and A2 become merged to MANET A. Static scheme still cannot support UDP 2 although it has an active gateway in MANET A. It is because the active gateway is not properly positioned; it is located on the right side of MANET A, and is out of the communication range of another

active gateway in MANET B. However, after the MANETs are merged, dynamic scheme elects one active gateway which is the best to guarantee inter-MANET connectivity. Thus dynamic scheme again supports *both* UDP flows after the gateway election.

Figure 4 shows UDP throughput of different schemes during simulation time and Table IV represents the averaged UDP throughput over the time. Note that as shown, dynamic case achieves 1.33Mbps and the improvement from dynamic gateway election compared to the static scheme is 84.72%.

C. Scenario 2: InterMR with Random Waypoint Mobility

First we evaluate the performance of InterMR with RWP mobility. Under RWP, sub-networks in the two MANETs are randomly partitioned and merged with each other. Figure 5 shows connectivity of active gateways in terms of the number of reachable destinations. We show the result with both static and dynamic gateway assignment.

As one can expect InterMR provides reachability numbers that are in between 'w/o InterMR' and 'Single DSDV' MANET. Also it shows a general trend that the reachability improves as more nodes acts as active gateways. Note that the single DSDV case only connects 17.31 nodes out of 50 nodes on average, which shows that the network density is sparse and even the single MANET is divided into multiple partitions.

We also confirm our intuition that the dynamic gateway election scheme will perform better than the static gateway assignment. Figure 5 demonstrates that the dynamic gateway mechanism effectively handles the partition isolation problem and improves the connectivity by up to 44.32% compared to the static case. In addition, the improvement on connectivity results in higher UDP throughput in the dynamic case compared to the static case shown in Figure 6 (by 50% – 112.2% improvement).

Finally, Figure 7 presents that the average number of hop counts between sources and destinations of UDP flows. In the 'w/o InterMR' case, the average number of hops is 1.36, since the source and destination of each UDP flows are mostly directly connected. As we increase the ratio of active gateways, both static and dynamic cases connect more sources and destinations of UDP flows with more number of hops. But it is encouraging that despite increased hop counts connectivity and application performance is better with inter-MANET connectivity.

D. Scenario 3: InterMR with Group Mobility

In this section, we evaluate InterMR with Reference Point Group Mobility [13]. For RPGM, we created 10 groups with 50 nodes and assigned five groups to belong to one MANET. Each group is composed of 5 nodes and one of them is the group leader. Except for the mobility model, the rest of simulation settings are same as in Section IV-A.

We notice several interesting points with group mobility test. First, the group mobility model scenario results in higher connectivity than the random mobility case. We conjecture that this must be because, nodes move as groups and this provides more opportunity for a MANET to stay together and makes it more likely that even a single gateway can contribute a lot. Compared to the random mobility model, the group mobility model has significantly higher connectivity: by up to 110% in static case and 93% in dynamic case. UDP throughput in Figure 9 also shows that group mobility provides better performance. This is a good news because we expect nodes in the same MANET will likely move as a group as in coalition military units.

In the group mobility case also, we find that dynamic gateway election mechanism results in significant performance benefit in terms of connectivity and throughput, compared to the static gateway assignment. The performance gain is especially pronounced when the number of gateways is small. When there are only 2 gateways (out of 50 nodes) the improvement by dynamic gateway election is about 68% compared to the static case.

V. Control Overhead Analysis

In this section, we offer analytical insights of the incurred control overhead of InterMR. We aim to justify the feasibility of InterMR framework by a qualitative estimate of the control overhead. In practice, the overhead often depends on a variety of network parameters, which makes analysis difficult. Hence, in this section we rely on several generic assumptions on the intra-MANET routing protocols and mobility behavior. Our analytical insights provide simple insights to support the feasibility of InterMR, and is complementary to the full performane evaluations of overhead in a more realistic MANET environment in Sec IV.

Similar to the overhead analyses of other wireless routing protocols [9], [26], we do not model the complex behaviors of MAC layer, route caching, and the interaction of routing policies of different MANETs. Nor do we assume loss or retransmission of control packets. But unlike [9], [26], we explicitly consider the impact of mobility on the control overhead of routing protocols.

We consider inter-MANET routing over two generic types of MANETs: proactive and reactive. There are three major types of overhead:

1) *Intrinsic proactive overhead*: Link state maintenance in a proactive MANET to detect network partition or merging, which is intrinsic, even without InterMR.

2) *Reactive overhead*: Beaconing among intra-MANET gateways in a reactive MANET to detect network partition or merging.

3) *Inter-MANET overhead*: The communications among inter-MANET and intra-MANET gateways to announce and update MANET-level reachbaility information.
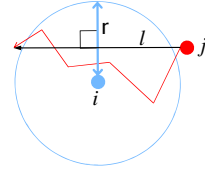

Fig. 11. The distance of a zigzag trajectory of a node can be lower bounded by a straight line walk.

Our analysis provides a basic estimate of the control overhead, which can be improved significantly, for instance, by suppression of probing, adaptive adjustment of probing interval. We show that the overhead incurred at each gateway for inter-MANET routing operation can be relatively moderate.

A. Settings and Notations

For the convenience of analysis, we assume the gateways in each MANET are fixed. We consider a homogeneous setting: each (proactive or reactive) MANET has the same number of nodes n and gateways k, with the same transmission radius r and mobility model (see Table V). If one node moves away from the transmission radius of other, then the link between them breaks.

Also, we ignore the effect of boundary and assume nodes are confined to a finite boundary-free unit area (e.g. on the surface of a sphere). The mobility model is the random waypoint model: a node uniformly and randomly picks a destination in the area, and moves to the destination with a speed uniformly distributed in range $[v_{\min}, v_{\max}]$, where $v_{\min} > 0$.

Because it is a boundary-free area, the stationary distribution of the location of a node is uniform (If there is a boundary, the stationary distribution of the location is more complicated and may not be uniform [14]). At a random time, the snapshot of the nodes in a MANET gives a uniform random geometric graph (denote as $\mathcal{G}(n, r)$).

Symbol	Defintion
m_{pro}, m_{rec}	The number of proactive, or reactive MANETs
n	The total number of nodes in a MANET
k	The number of gateways in a MANET
r	Transmission radius
$v_{\min}$, $v_{\max}$	Minimum and maximum speed of a node

TABLE V

B. Link State Update Rate

Let the average link lifetime be $\bar{T}_{\text{lk}}$, which is measured from the moment that a link is established when the distance between a pair of nodes is just within transmission radius r, to the moment that one node moves away from another for more than r. We will provide a simple lower bound of $\bar{T}_{\text{lk}}$ in V-F.

Since the nodes are in constant movement, links establish and break from time to time. The control overhead of intra-MANET routing protocols is due to regularly updating link state in the MANET. This creates both overhead to the link state maintenance in proactive MANETs and beaconing among intra-MANET gateways in reactive MANETs.

Let $\bar{E}$ be the average number of links in a MANET. Then the update rate for link breakages is $\bar{E}/\bar{T}_{\text{lk}}$. Since the mobility process of nodes is stationary, the probability rate of link establishment balances the one of link breakage. Hence, the average numbers of link establishments per second due to mobility in a MANET is the same as the one of link breakages. Hence, the update rate for link establishments is also $\bar{E}/\bar{T}_{\text{lk}}$. Therefore, the total rate of link state update is $2\bar{E}/\bar{T}_{\text{lk}}$.

C. Intrinsic Proactive Overhead

Each node periodically broadcasts probe packets to its neighbors. Based on the received probe packets, each node announces a new link-state/distance-vector packet, which then will be propagated throughout the MANET. Let λ_{prb} be the rate of probe packet by each node. The detected rate

of link state changes cannot be faster than λ_{prb}. Hence, it follows the below preposition.

Preposition 1: The proactive overhead H_{pro} is:

$$H_{\mathrm{pro}} = n \cdot \min\left(\lambda_{\mathrm{prb}}, \frac{2\bar{E}}{\bar{T}_{\mathrm{lk}}}\right) \tag{1}$$

This is the intrinsic proactive overhead by InterMR to detect network partition or merging.

From the well-known result in [19], we set transmission radius $\mathsf{r} = \Omega(\sqrt{\log n/n})$ to maintain full connectivity in the MANET. Also, [4] (Lemma 10) shows that for a random geometric graph if $\mathsf{r} = \Omega(\sqrt{\log n/n})$, then the degree of each node is $n\pi \mathsf{r}^2(1 + \mathrm{o}(1))$ with high probability. Thus, $\bar{E} = n^2\pi \mathsf{r}^2(1 + \mathrm{o}(1))/2$. Hence, we obtain:

$$H_{\mathrm{pro}} = \Theta\left(n \cdot \min\left(\lambda_{\mathrm{prb}}, \frac{n\log n}{\bar{T}_{\mathrm{lk}}}\right)\right) \tag{2}$$

D. Reactive Overhead

In InterMR beaconing among intra-MANET gateways is to detect network partition or merging. Since every pair of intra-MANET gateways maintains beacon sessions, the overhead scales as $k(k-1)$. Let λ_{bea} be the beaconing rate between a pair of intra-MANET gateways. The detected rate of network partition or merging cannot be faster than λ_{bea}.

Let $\bar{D}$ be the diameter (i.e. the maximum number of hops of a shortest path). The rate of link state changes for the path used for beaconing is bounded by $\Theta(2\bar{D}/\bar{T}_{\mathrm{lk}})$. Hence, it follows the below preposition.

Preposition 2: The reactive overhead H_{rea} is:

$$H_{\mathrm{rea}} = k(k-1) \cdot \min\left(\lambda_{\mathrm{bea}}, \frac{2\bar{D}}{\bar{T}_{\mathrm{lk}}}\right) \tag{3}$$

From [12], it is shown that for a random geometric graph, if $\mathsf{r} = \Omega(\sqrt{\log n/n})$, then the diameter is upper bounded by $2(1 + \mathrm{O}(\sqrt{\log\log n/\log n}))/\mathsf{r}$ with high probability. Hence, if we set $\mathsf{r} = \Theta(\sqrt{\log n/n})$, we obtain:

$$H_{\mathrm{rea}} = \mathrm{O}\left(k(k-1) \cdot \min\left(\lambda_{\mathrm{bea}}, \frac{1}{\bar{T}_{\mathrm{lk}}}\left(\frac{\sqrt{n}}{\sqrt{\log n}} + \frac{\sqrt{n\log\log n}}{\log n}\right)\right)\right) \tag{4}$$

We note that as compared to the intrinsic proactive overhead in Eq. (2), we normally set k and λ_{bea} lesser than $\sqrt{n}$ and λ_{prb}. Thus, the reactive overhead, Eq. (4), is significantly smaller compared to the intrinsic proactive overhead. Also, beaconing in the reactive overhead of route maintenance can be piggy-backed on other data traffics, which can be much smaller than the estimate.

E. Inter-MANET Overhead

Suppose there are m_{pro} proactive MANETs and m_{rea} reactive MANETs. The inter-MANET control packets from one intra-MANET gateway will be multicast to other intra-MANET gateways. Let λ_{int} be the exchange rate between a pair of inter-MANET gateways. Then, the inter-MANET overhead, H_{int}, in a multi-MANET MANET is:

$$H_{\mathrm{int}} = k\lambda_{\mathrm{int}}(m_{\mathrm{pro}} + m_{\mathrm{rea}}) \cdot H_{\mathrm{RT}} \tag{5}$$

where H_{RT} is the size of MANET-level route table of path vector protocol, which can be estimated as the size of MANET-level path vector entries to all the destinations: $H_{\mathrm{RT}} = \mathrm{O}(n(m_{\mathrm{pro}} + m_{\mathrm{rea}}))$. Note that inter-MANET overhead can be improved significantly by using dynamic gateway selection, which reduces the exchanges of route tables between inter-MANET gateway pairs if gateways are optimally elected.
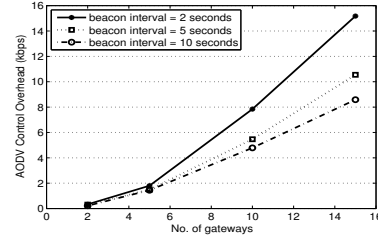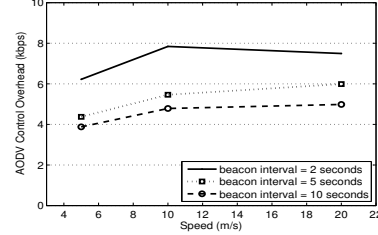

Fig. 12. AODV overhead when speed = 10 m/s

Fig. 13. AODV overhead when no. of gateways = 10

F. Average Link Lifetime $\bar{T}_{\mathrm{lk}}$

Although average link lifetime has been studied in [23], there is no convenient formula given so far for efficient evaluation. In this section we provide a simple lower bound of $\bar{T}_{\mathrm{lk}}$ for the random waypoint model.

Consider two moving nodes i, j in Figure 11. We can lower bound the distance of a zigzag trajectory by j by a straight line walk (as a chord) that cuts across the circular transmission range of i. The link lifetime is lower bounded by the time taken to walk along the chord.

Preposition 3: The average link lifetime is lower bounded by:

$$\bar{T}_{\mathrm{lk}} \geq \frac{\pi\mathsf{r}}{2} \frac{\sqrt{\log v_{\max} - \log v_{\min}}}{\sqrt{(v_{\max})^2 - (v_{\min})^2}} = \Theta\left(\frac{\mathsf{r}\sqrt{\log v_{\max}}}{v_{\max}}\right)$$

Proof: By the isotropy of random waypoint model, the trajectory can take place at any angle. We fix an orientation at i, and assume that the straight line walk hits the radius at a right angle. Since random waypoint model is uniform in space, the straight line walk can hit the radius in uniform distribution. Let $\bar{l}$ be the average distance a random chord that cuts across the circular transmission range of i. We obtain:

$$\bar{l} = 2\int_0^{\mathsf{r}} \frac{\sqrt{\mathsf{r}^2 - l^2}}{\mathsf{r}}\,\mathrm{d}l = \frac{\pi\mathsf{r}}{2}$$

Since two nodes are both moving, let v_{rel} be the average relative speed between i and j. By cosine formula,

$$(v_{\mathrm{rel}})^2 = (v_i)^2 + (v_j)^2 - 2v_iv_i\cos\theta$$
$$\Rightarrow \quad \mathbb{E}[(v_{\mathrm{rel}})^2] = \mathbb{E}[(v_i)^2] + \mathbb{E}[(v_j)^2] - 2\mathbb{E}[v_iv_i\cos\theta]$$

where θ is the angle between i and j. Since the angle is independent of the speed, we obtain:

$$\mathbb{E}[(v_{\mathrm{rel}})^2] = 2\mathbb{E}[(v_i)^2] - 2\mathbb{E}[v_iv_i]\int_0^\pi \frac{\cos\theta}{\pi}\,\mathrm{d}\theta = 2\mathbb{E}[(v_i)^2]$$

By Jensen's inequality,

$$\mathbb{E}[v_{\mathrm{rel}}] \leq \sqrt{\mathbb{E}[(v_{\mathrm{rel}})^2]} = \sqrt{2\mathbb{E}[(v_i)^2]}$$

Although when i picks its speed initially v_i is uniformly distributed in $[v_{\min}, v_{\max}]$, when we observe over time v_i is not a uniform random variable. Because the faster nodes are less likely to be observed as they finish the trips more quickly. The density of observed distribution of v_i should be (see [14]):

$$f(v) = \frac{v^{-1}}{\int_{v_{\min}}^{v_{\max}} v'^{-1} \, \mathrm{d}v'} = \frac{v^{-1}}{\log v_{\max} - \log v_{\min}}$$

Therefore,

$$\mathbb{E}[(v_i)^2] = \frac{\int_{v_{\min}}^{v_{\max}} \dfrac{v^2}{v} \, \mathrm{d}v}{\log v_{\max} - \log v_{\min}} = \frac{(v_{\max})^2 - (v_{\min})^2}{2(\log v_{\max} - \log v_{\min})}$$

The average link lifetime is lower bounded by:

$$\bar{T}_{\mathsf{lk}} \geq \frac{\bar{l}}{\mathbb{E}[v_{\mathrm{rel}}]} \geq \frac{\pi \mathsf{r}}{2} \frac{\sqrt{\log v_{\max} - \log v_{\min}}}{\sqrt{(v_{\max})^2 - (v_{\min})^2}} \quad \blacksquare$$

It follows that the link state update rate is $\mathrm{O}\left(\frac{\bar{E} v_{\max}}{\mathsf{r} \sqrt{\log v_{\max}}}\right)$. For instance, if we set transmission radius $\mathsf{r} = \Omega(\sqrt{\log n / n})$ to maintain full connectivity in the MANET, then the link state update rate is $\mathrm{O}\left(\frac{n^{\frac{3}{2}} \sqrt{\log n} \, v_{\max}}{\sqrt{\log v_{\max}}}\right)$. For instance, if we set transmission radius $\mathsf{r} = \Omega(\sqrt{\log n / n})$ to maintain full connectivity in the MANET, then the link state update rate is $\mathrm{O}\left(\frac{n^{\frac{3}{2}} \sqrt{\log n} \, v_{\max}}{\sqrt{\log v_{\max}}}\right)$.

G. Evaluations

In this subsection, we present simulation evaluations to corroborate our analysis. We use 50 nodes with random waypoint model on a $1000 \times 1000 m^2$ area. We set the transmission radius as $250m$. We measure the control overhead by reactive overhead by AODV which is triggered by gateway beaconing (i-InterMR). We study the impacts of the number of gateways, the beacon interval, and the speed of node mobility.

In Figure 12, the AODV overhead almost scales quadratically as the number of gateways (indicated by Eqn. (3)), while in Figure 13, it scales modestly as the averaged speed. The later can be explained by the fact that the link state update rate is $\mathrm{O}\left(\frac{\bar{E} v_{\max}}{\mathsf{r} \sqrt{\log v_{\max}}}\right)$ (from Theorem 3), and the averaged speed is bounded by the maximum speed $v_{\max}$.

VI. CONCLUSION

In this paper, we presented a novel inter-MANET routing protocol to support communication across heterogeneous MANETs. We identified that the technical challenges for designing a viable inter-MANET routing solution for MANETs are fundamentally different from conventional inter-MANET routing in wired network using BGP. In particular, we identified several major challenges, namely lack of a name server, dynamic network topology change, non-existence of well-defined boundaries, and heterogeneous intra-MANET routing protocols. After careful evaluation of these challenges, we designed an attribute based inter-MANET routing protocol, called InterMR. The protocol design includes the key functionalities of gateways to support seamless interaction across different MANETs. In addition, we proposed an attribute based addressing scheme based on bloom filter which guarantees unique MANET addresses and transparent merge/split operations, and; a distributed dynamic gateway election algorithm that can significantly improve inter-MANET connectivity and application performance by adaptively electing active gateways to cope with topological changes. We implemented the protocol in a packet level network simulator and systematically evaluated it under realistic MANET scenarios. From the simulation

results we showed that our protocol provides effective inter-MANET communication among heterogeneous MANETs, and particularly that the dynamic gateway election scheme significantly performs better than the static mechanism.

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