ORBIT Mobility Framework and Orbit Based Routing (OBR) Protocol for MANET

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***Abstract*— A major hurdle in evaluating routing protocols for a Mobile Ad Hoc NETwork (MANET) is the appropriate modeling of the mobility of wireless nodes. Although the pure random nature of the Random Waypoint model lends itself for theoretical study of MANET protocols, it is not suitable for modeling the movements of mobile nodes in real scenarios. To this end, several entity, group and scenario based mobility models and frameworks have been proposed in literature for representing node mobility. Some of these models cater to only short term applications of ad hoc networks (e.g., disaster, military), while others are based on complex scenario parameters (e.g., buildings, pathways).**

In this paper, we propose a novel mobility framework called ORBIT. In addition to generating a more practical mobility pattern based on sociological movement of users, ORBIT can also integrate all the work mentioned above into a single framework. The proposed ORBIT framework is applicable to all kinds of wireless networks (cellular, ad hoc etc.) and is also capable of generating different models to suit either short term or long term network mobility in various scenarios. We also propose an Orbit Based Routing (OBR) protocol for MANETs, which takes advantage of the ORBIT framework and outperforms other routing protocols like Dynamic Source Routing (DSR) and Location Aided Routing (LAR).

***Index Terms*— Mobility models, Routing protocol, Ad hoc wireless networks, Performance analysis**

I. INTRODUCTION

A wireless mobile ad hoc network (MANET) is an infrastructure less group of wireless mobile devices that forward packets for one another. The main challenge in evaluating protocol performance for such networks is the appropriate representation of the mobility pattern of the mobile nodes. Random Waypoint [1] is the most liberally used mobility model for evaluating a large number of MANET routing protocols. In this model, a node randomly chooses a destination point within the terrain and approaches it linearly with a velocity randomly selected from a specified range. On reaching the point, it pauses for a specified time and then repeats the process. Although such a random movement is simple to implement and maybe suitable for theoretical study and analysis, it is not an appropriate representation of real life mobility. In reality, users (and their PDAs/Laptops, which serve as the nodes in a MANET) move with some purpose in mind (e.g., going to work), and under certain constraints (e.g., obeying traffic laws) resulting in certain amount of determinism. To account for this, several mobility models/frameworks have been proposed that can be categorized as either *Entity based*, *Group based*, or *Scenario based*. The *Entity based* models are driven by the individual node characteristics. The *Group based* models concentrate on the collective movement of a group of nodes that deviate marginally from the characteristics of a leader node. The *Scenario based* models account for the geographical constraints on real life movement.

In this paper, we propose a novel framework called ORBIT. Our work is inspired by the fact that an 'orbit' is the most natural form of motion in both the microscopic world of molecules and in the planetary universe. Such an 'orbit' can also be observed in the sociological movement pattern of users who move according to some disciplined routine. In addition to the orbital mobility pattern, the proposed ORBIT framework can also integrate all other mobility models into a single framework. As a result, ORBIT is not only practical for both cellular and ad hoc networks, but also a general framework to model both short term and long term network mobility.

We also study the opportunities in routing within a MANET presented by the proposed ORBIT framework. Within the two categories of routing protocols described in literature: *Pro-active* and *Reactive*, the latter is more suited for highly mobile ad hoc networks due to its ability to cope with rapidly changing network topologies. Dynamic Source Routing (DSR) [1] was among the earliest proposed reactive protocols, in which a data packet to a destination with an unknown route causes the source to flood all the neighboring nodes with a query to discover the desired route. DSR is simple to implement, but suffers from a high amount of link breakage in the face of mobility. The authors of [2] suggested a Location Aided Routing (LAR) protocol, in which the source tries to restrict the flooding required by estimating the approximate location of the destination. However, it may have to repeatedly flood a larger area until it either discovers a path to the destination, or floods the entire terrain. As a result, LAR usually suffers from a high control overhead.

In this paper, we propose an Orbit Based Routing (OBR) protocol for MANETs, which takes advantage of the practical 'orbital' mobility pattern in determining a fixed set of likely regions containing any node. It differs from the other protocols by uniquely integrating an acquaintance based distributed location database with the mobility characteristics of the proposed ORBIT framework. We perform simulations to compare OBR against DSR and LAR in Scheme 1 (LAR1), and our results show OBR to have a higher data throughput than both

DSR and LAR1, and a much lower control overhead than LAR1 signifying higher energy efficiency in power constrained MANETs.

The rest of the paper is outlined as follows. In Section II, we motivate our work by discussing the sociological movement pattern of humans, as well as other natural orbits. In Section III, we describe the details of the proposed ORBIT mobility framework, and in Section IV, we demonstrate ORBIT's versatility by generating several example models to suit different scenarios. In Section V, we analyze the characteristics of our models using some of the metrics suggested in [3]. In Section VI, we describe the proposed Orbit Based Routing (OBR) protocol, and in Section VII we study the effect of our mobility models on the performance of OBR (along with DSR and LAR1). In Section VIII, we establish the superiority of OBR over DSR and LAR1 through simulations. In Section IX, we present a detailed description of other related mobility models and frameworks, and contrast them with ORBIT. We conclude this work in Section X.

II. Sociological Movement Pattern

In the real world, people live within societies, where their movement is subject to social constraints (e.g., following traffic regulations). Accordingly, although it is hard to determine the exact route taken by an individual at every turn, from a high level perspective, any person's movement exhibits a certain pattern that is repeated in some sequence. For example, an employee in an office may not always take the same path from his seat to a shared printer, but he is likely to repeat that movement a number of times during a day. Thus, even when we cannot determine the employee's location at a specific time, by studying his daily job routine, we can identify a list of possible places (e.g. cubicle, cafeteria) for locating him. In other words, there is an 'orbital' movement between these points of interest for this person.

This orbital movement pattern is also observed in a larger context. For example, on an average weekday, the employee could leave home for office in the morning, visit the gymnasium in the evening, and return home at night. Although we cannot predict the exact time or route taken by the person from one point to another on any given day, there is a number of fixed points of interest that are visited in some order, day after day, forming a high level 'orbit'. Similarly, the employee might stay in his home town for a few weeks and visit friends and family in other cities over some weekend, forming yet another higher level nation-wide 'orbit'.

In short, the sociological movement pattern of humans is observed to be a collection of orbits at different levels of hierarchy, where each orbit comprises of a list of areas of interest and the movement in between them. Each such area along a high level orbit in turn contains a low level orbit consisting of a movement among a list of smaller areas of interest and so on, as illustrated in Figure 1. At each level of the hierarchy, the mobility along the orbits differs in terms of speed from one area to another, and the pause time in each area.

Interestingly, an 'orbit' is one of the most natural form of motion observed in the microscopic world of molecules, and

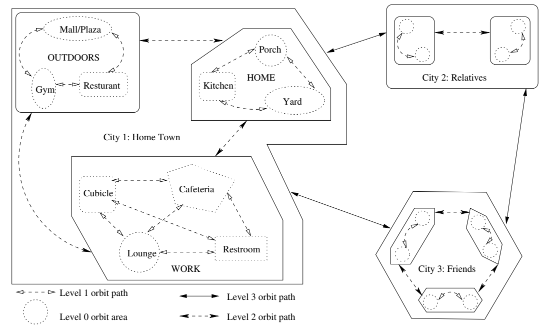

Fig. 1. The sociological orbit

in the planetary universe as well. In fact, one may map certain characteristics of the natural orbits in these two extremes, to that of the sociological orbit described above.

A. *Electron Mobility*

Electrons of an atom orbit the atomic nucleus in different energy levels. Each atom is considered stable with a specific number of electrons in them. If this number increases or decreases, it becomes reactive, in which case electrons are exchanged in between oppositely charged atoms to attain stability. In our society, job opportunities and inexpensive accommodation may cause an influx of people into a city. This may slowly saturate the place, leading to a scarcity of jobs or a high cost of living which in turn prompts people to move out to other cities that offer better opportunities. In this way, over a long period of time, our society tries to maintain some stability across its city based social nuclei.

B. *Planetary Motion*

All planets along with their satellites display a time and space based hierarchical orbital model. The moon revolves around the earth in a small orbit, lasting a month. The earth revolves around the sun in a larger orbit, lasting a year. The sun itself revolves around the milky way in a huge orbit of its own, lasting around 226 million years (a cosmic year). Similarly, we find people moving within a small area (at home, work, etc.) for a few hours, forming small orbits at different parts of the day. A high level orbit, along which a person moves from one such area to another lasts for days or weeks. Over a period of months or years, a person may travel between cities along yet another higher level orbit. To the best of our knowledge, there exists no mobility model or framework that captures this hierarchical orbital movement pattern, despite its practicality.

III. The ORBIT Mobility Framework

Keeping the sociological orbit in mind, we developed a mobility framework called ORBIT that incorporates the orbital movement pattern to easily generate practical models suiting various scenarios. The basic building blocks in ORBIT are the different levels of orbit. The versatility of ORBIT is in the fact that the mobility modeler in each orbital level may be viewed as a black box outputting node mobility traces, given inputs for that specific level. We model the lowest level orbit (level

0 in Figure 1) a bit differently than the higher level ones in terms of the output generated. More specifically, our black box for level 0 orbit takes as input a smallest area of interest and a given duration, and generates mobility traces within the area for that duration. In contrast, at the higher levels, the black box takes as input a list of areas of interest and generates a visiting sequence, as well as the mobility trace from one area to another. The exact nature of the traces generated by the black boxes at any level depend on the mobility model implemented within it, and hence is user defined. Figure 2 suggests a few of the existing mobility models that can be used in our framework at different hierarchical levels (references for these models are in Section IX). For example, at level 0, we could use the Manhattan model to generate mobility traces within a city, and at level 1, apart from generating a sequence of cities to visit, we could use the Freeway model to generate inter-city movement. This is an additional strength of the proposed ORBIT framework, which can integrate all other models into a single domain providing practical models that are not only highly detailed, but are also capable of accommodating geographic hierarchies of cities and nations. Moreover, by appropriately fixing the area and duration of the lowest level 0 orbit, it is possible to simulate both small scale and large scale networks within the same framework.

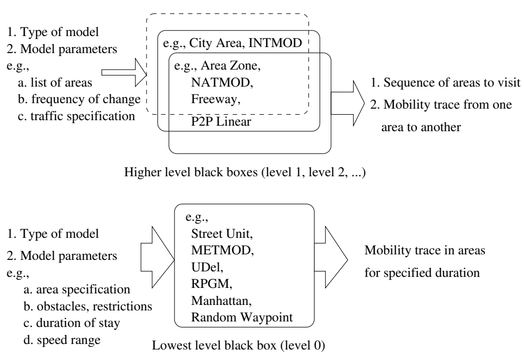

Fig. 2. The ORBIT framework (see Section IX for model references)

A. The Simplified ORBIT Framework

To facilitate our discussion, we consider a simplified ORBIT with three hierarchical orbital levels. It is worth noting that given the generality of the ORBIT framework as discussed earlier (and in Figure 2), the following choices and assumptions made, serve only to simplify our quantitative analysis.

At the lowest level, we assume a rectangular area of interest, referred to as a *Hub*. For simplicity, we choose the Random Waypoint model within this area, but modify it slightly to fix the average speed decay problem by setting only non-zero minimum speed, as suggested in [4]. We refer to the movement inside the Hub as a *Local Area Orbit (LAO)*. For the next higher level, we consider a random selection process from a list of given Hubs. To move from one Hub to another, we choose to implement a simple model where a node picks a random point inside the new Hub and moves linearly towards it from its current location. We call this model as *P2P Linear*, and refer to this level of mobility as a *Medium Area Orbit (MAO)*. For the highest orbital level called the *Global Orbit (GO)*, we just consider a change in the list of Hubs given to the lower MAO. In this simplified framework, the MAOs may either overlap with a common Hub as shown in Figure 3, or may also remain disjoint as in Figure 1.

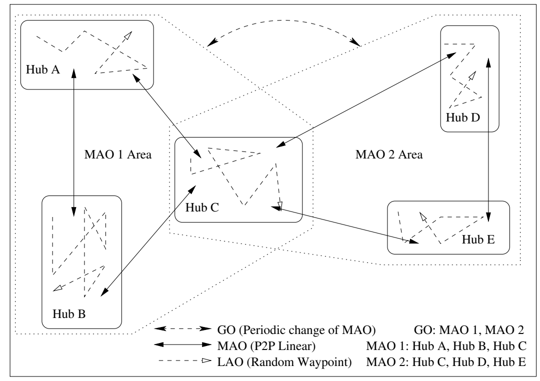

Fig. 3. The simplified ORBIT mobility framework

B. Simplified ORBIT Parameters

Considering the simplified ORBIT framework as an example, the parameters required to describe the framework could be divided into *3* sections, as depicted in Table I.

TABLE I
ORBIT PARAMETERS

Category	Parameter
Global Attributes	Total Hubs Hub Size (min, max) Hub Stay (min, max) Global Pause (min, max)
MAO Specific	Node Hubs (min, max) Node Speed (min, max)
LAO Specific	Hub Pause Hub Speed (min, max)

A Hub is assumed to be a rectangular area within the simulation terrain, with sides bounded by *Hub Size*. Initially, a specific number (bounded by *Node Hubs*) of Hubs is assigned to each node as part of its MAO. Nodes travel along their MAO from one Hub to another with speeds bounded by *Node Speed*. On reaching a Hub, a node moves according to the Random Waypoint model with speeds bounded by *Hub Speed* and pauses for *Hub Pause* amount. Each Hub requires a visiting node to stay for a time bounded by *Hub Stay*, which is also referred to as the *LAO Timeout*. When this timeout occurs, the node randomly selects another Hub from its list and moves towards it along its MAO, and initiates a fresh LAO upon reaching it. The MAO itself expires after a duration bounded by *Global Pause*, also referred to as the *MAO Timeout*, whence a fresh list of Hubs are assigned to the node to start a new MAO. Successive MAOs form the GO for the node. The actual speed limits in the LAO and the MAO will depend on the type of scenario being modeled.

IV. ORBIT BASED MOBILITY MODELS

In this section, we demonstrate the applicability of the models generated by our framework. We show that common mobility models like Random Waypoint and Random Walk can be trivially produced by our simplified framework by appropriately choosing values for our ORBIT parameters. In addition, we generate several new models as examples, which may be used to simulate realistic scenarios.

A. Random Waypoint and Random Walk

If we let a single Hub cover the entire terrain, and set the LAO Timeout to the simulation time, all the nodes will follow Random Waypoint in the single Hub. On the other hand, the entire terrain can be tiled into Hubs in such a way that a node can go from one Hub center to any adjacent Hub center in a single simulation step. By setting the LAO Timeout to zero, and selecting the visiting sequence to go through only adjacent Hubs, a Random Walk is generated. Figure 4 illustrates both these scenarios. Although these examples are trivial, they serve to illustrate the capacity of ORBIT to emulate existing mobility models that are commonly chosen for evaluating MANET protocols.

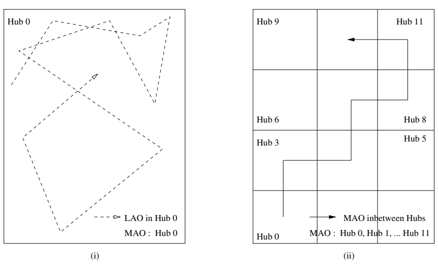

Fig. 4. (i) Random Waypoint (ii) Random Walk

B. Random Orbit

Among all the new models to be described, this is the most general. Figure 5 illustrates this Random Orbit model, where we assume each Hub to be a rectangular region with varying sizes. In each Hub, nodes move in an LAO with LAO Specific Parameters, and use the MAO Specific Parameters to travel from one Hub to another in the same MAO. On an MAO Timeout, a new set of Hubs are chosen to form a new MAO. While in an MAO, nodes visit their Hubs in a random sequence. This model is useful for representing regular city traffic. Each Hub represents an office or residential area, where people move around in their sociological orbits. We observe pedestrian traffic inside Hubs, and faster vehicular traffic in between Hubs. The speed ranges for the LAO and the MAO are chosen according to real life speeds summarized in Table II.

C. Uniform Orbit

This model is similar to Random Orbit, except for the setup of the Hubs. More specifically, unlike in the previous model, the entire terrain is divided into a grid of Hubs, with no

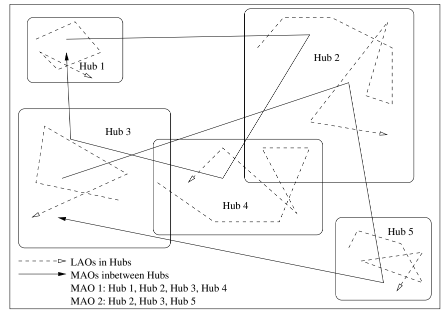

Fig. 5. Random Orbit: City Model

Hubs overlapping with any other as seen in Figure 6(i). Such a model may be used to simulate smaller scenarios like a School building, which is divided into a set of non overlapping classrooms. Students keep moving from one classroom to another along an MAO, and spend some time in each room along an LAO. The MAO might change after weeks/months along a GO.

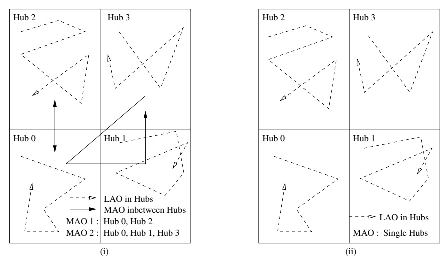

Fig. 6. (i) Uniform Orbit: School (ii) Restricted Orbit: Office

D. Restricted Orbit

This model is similar to Uniform Orbit, except that in this model, each MAO consists of a single Hub. In effect, an MAO is identical to an LAO, and there is no inter-Hub movement as shown in Figure 6(ii). This model is useful in simulating an office building scenario, that is made up of several non overlapping departments (or Hubs). Employees belonging to a particular department generally restrict themselves to a particular office space, thereby having no inter-Hub movements along the same MAO. Over time, their work might require them to shift to a different department, causing their MAO to change along their GO.

E. Overlay Orbit

In this model, we have the same setup as the Restricted Orbit. However, we overlay an extra Hub on top of the grid of Hubs, that spans the entire terrain. Movement in this model's MAO is also restricted to a single Hub. However, due to the overlaying nature of the extra Hub, nodes in this Hub move through all other smaller Hubs as seen in Figure 7. Such a model is useful for simulating exhibition/convention scenarios where a fixed number of organizers/presenters set their stalls up in small non-overlapping sections, while general people/attendees move across from one stall to another.

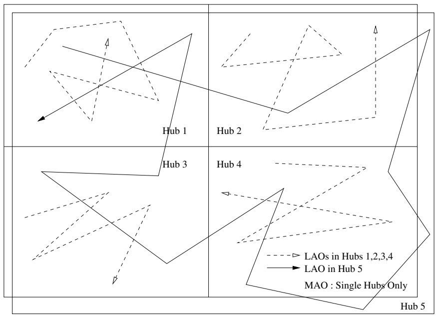

Fig. 7. Overlay Orbit: Exhibition/Convention Area

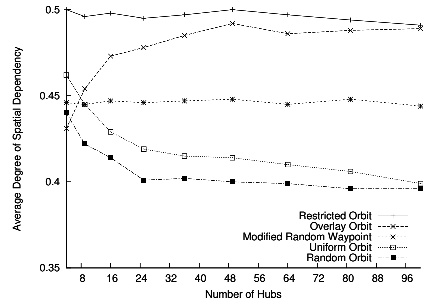

Fig. 8. Spatial Dependence vs. Number of Hubs

V. Analysis of Model Characteristics

In this section, we analyze the models generated by the proposed ORBIT framework using a few of the protocol independent metrics defined in [3], which were shown to affect the basic building blocks of different routing protocols, thus accounting for the effect of mobility models on protocol performance. Our motivation for this analysis is to illustrate that our models generated as examples, differ with respect to these metrics when any ORBIT parameter is varied, providing multiple choices for modeling mobility in different scenarios. We choose to vary the number of Hubs in our study, since this also causes the Hub sizes to vary in all our grid based models (i.e. all except Random Orbit). Although our modified Random Waypoint model has a single Hub and yields a constant result when the number of Hubs varies, it is included as a reference point in our simulations. We perform our simulations in GloMoSim [5] with 100 nodes in a 1000 x 1000 sq. meter area for 1000 seconds. Each node is assumed to have a Radio Range of 250 meters. ORBIT parameters are used as follows.

- Hub Size (min/max) = (150/250)m (Random Orbit)
- Hub Stay (min/max) = (50/100)s
- Global Pause (min/max) = (250/500)s
- Node Hubs (min/max) = (1/Total Hubs)
- Node Speed (min/max) = (10/30)m/s
- Hub Speed (min/max); Pause = (1/10)m/s; 1s

To analyze our models, we use the average degrees of spatial and temporal dependency as the mobility metrics, and the average number of link changes and link duration as the connectivity graph metrics. For a detailed description of the metrics, the reader is referred to [3]. No single metric serves as the determining factor in choosing one model over another.

A. Mobility Metrics

1) Average Degree of Spatial Dependence: Spatial Dependence indicates the similarity in the velocities of two nodes that are within a specific range from each other, which is chosen to be $2 * (RadioRange)$ in our simulations. Since Restricted Orbit and Overlay Orbit do not allow inter-Hub movements, nodes in the same Hub follow the same Hub parameters for a long time, resulting in a high spatial dependence as seen in Figure 8. Random Orbit and Uniform Orbit support inter-Hub movements and hence have a lower value for this metric, while our modified Random Waypoint has an intermediate value.

2) Average Degree of Temporal Dependence: Temporal Dependence indicates the similarity in the velocities of a node within a specific time interval, which was taken to be 20 seconds in our simulations. In Random Orbit, the Hub sizes are not affected by the number of Hubs, unlike in the other models, but the amount of overlap among Hubs increases sharply. Due to this overlapping, the inter-Hub movements end up being short (a node quickly reaches one Hub from another), similar to the intra-Hub movements causing frequent changes in mobility and leading to a low temporal dependence as seen in Figure 9. In our modified Random Waypoint, nodes have a single LAO where a slower speed change results in a high value for this metric. For the remaining models, a larger number of Hubs means a larger number of different Hub parameters that a node is subject to, leading to a steady decrease in the temporal dependence with an increase in the number of Hubs.

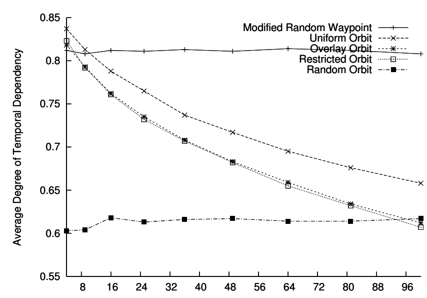

Fig. 9. Temporal Dependence vs. Number of Hubs

B. Connectivity Graph Metrics

1) Average Number of Link Changes: This is the average number of times a link between two nodes (that ever existed during the entire simulation) comes up from being down. Since in Restricted Orbit and Overlay Orbit nodes are confined to particular Hubs, the probability of a link between two nodes in the same Hub breaking (and then coming up later) is small. In our modified Random Waypoint, links that would break when two nodes move away, have a low probability of coming up later as nodes move slowly in the entire terrain. In Random Orbit and Uniform Orbit, a link that is formed when two nodes visit a common Hub may break when one of them moves away, but has a high probability of coming up again when they meet later in the common Hub. In Random Orbit, these nodes may re-form the link even if they are in different but overlapping Hubs, thus showing the highest value for this metric in Figure 10.

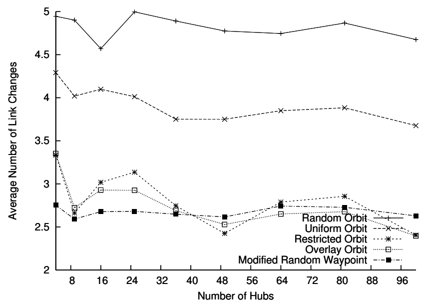

Fig. 10. Link Changes vs. Number of Hubs

2) Average Link Duration: This is the average time a link between two nodes stays up. The restricting nature of Restricted Orbit and Overlay Orbit proves beneficial to link stability. Moreover, with an increase in the number of Hubs, the Hub sizes decrease causing the nodes to huddle even closer, increasing link duration as seen in Figure 11. The inter-Hub movements supported by Random Orbit and Uniform Orbit causes link breaks to happen more often, while our modified Random Waypoint shows an intermediate value.

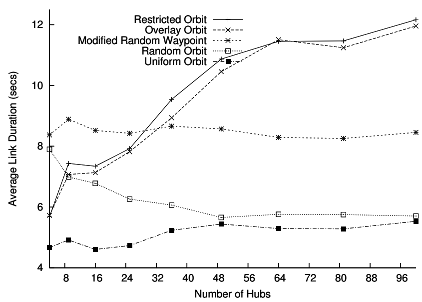

Fig. 11. Link Duration vs. Number of Hubs

VI. ORBIT BASED ROUTING (OBR) PROTOCOL

So far, we have described the realistic modeling capability of the proposed ORBIT framework. The orbital movement pattern also provides new opportunities to design efficient routing protocols. In this section, we describe our Orbit Based Routing (OBR) routing protocol that is among the first of its kind to the best of our knowledge, to make use of mobility information at the network layer.

Routing in MANET is a challenging problem, and the task of locating a node and maintaining a path to it becomes increasingly difficult in the face of node mobility. Literature has proposed several routing protocols for MANET, but due to the adoption of Random Waypoint model in the performance study of these protocols, no useful assumptions about the underlying mobility were made in the protocol design. In contrast, OBR tries to make use of the orbital mobility pattern in determining a set of likely regions containing a destination, as is described in detail below.

A. Protocol Overview

In continuation with our simplified analysis, we focus on a Hub level routing in the simplified ORBIT. Several motivations and advantages of *peer collaboration* were discussed by the authors in [6]. Accordingly, one of the basic concepts of OBR is to form a distributed location database among all nodes, where each node makes some acquaintances, and keeps track of their Hub lists within itself. This facilitates easy discovery of a destination with an unknown Hub list by a node via a network of its acquaintances, the acquaintances of each of its acquaintance, and so on. This concept is similar to that described in one of our earlier work [7], except that in OBR we take advantage of the underlying mobility information available through the ORBIT framework. This allows nodes to maintain Hub lists (that remain valid for a long time) of their acquaintances instead of their exact position, thereby reducing the overhead in *location updates* in the face of node mobility. More specifically, it is assumed that each node has a specific knowledge of the terrain in terms of the Hubs and their corresponding coordinates. It is also assumed that the mobile nodes are aware of their own location via the use of a GPS receiver [8], or other localization schemes. Each node periodically broadcasts its own coordinates and Hub list, and listens to the broadcasts made by other nodes, thereby learning of its neighbors. Each new neighbor becomes a new acquaintance and its corresponding Hub list is cached. Depending on the general value of the MAO Timeout observed in the scenario being modeled, an appropriate cache timeout value is chosen. The details of routing a packet in OBR is as follows.

B. Information Query Propagation and Response

When a source has *data* to send, it is directly transmitted to the destination if it is a neighbor. However, if it is not a neighbor, but an acquaintance with a valid Hub list in the source's cache, the *data* packet is forwarded towards that Hub list, as described in Section VI-C. If no information about the destination's Hub list is available, a *query* is sent out towards the Hub lists of a subset of acquaintances, chosen as described in Section VI-D. Such a transmission from a node to its acquaintance is referred to as a *logical hop*, which comprises of multiple physical hops determined by 'greedy geographic forwarding' [9], where each intermediate node chooses its next hop from amongst its neighbors who is closest to the destination's location than itself. An acquaintance responds to this *query* packet if it knows of a valid Hub list for the destination. If not, it forwards the *query* to a subset of its own acquaintances, carefully chosen as before. However, if the packet's logical hops exceed a specified threshold, it is dropped by the acquaintance instead of being forwarded to its own acquaintances. As an optimization, intermediate nodes are allowed to snoop into *query* packets and respond to them if possible. On receiving a *response*, the source caches the information and sends the *data* packet out towards the destination's Hub list.

C. Packet Transmission to a Hub List

In OBR, all packets (*query*, *response*, *data*, *update*) are sent from one node (source) towards the Hub list of another node (destination) that is contained in the packet header. The source tries to forward the packet towards a Hub in the list which is geographically nearest to its own Hub. From then on, each intermediate node performs greedy geographic forwarding to push the packet to the neighboring node that is closest to the intended Hub's center coordinates than itself. When a local maxima occurs, the packet is redirected towards the next unvisited Hub in the destination's Hub list. If the node responsible for this redirection was within the previously intended Hub, that Hub is marked inside the packet header as visited by the packet. This process is now repeated to forward the packet towards the center of the new Hub. In this way, a packet traverses from one Hub to another in the list, until either the destination is found, or all the Hubs in the list are visited.

To improve data accessibility, *data* packets are cooperatively cached at all intermediate nodes that forward the packet within a Hub to which it is intended. In this way, if the destination reaches a Hub after the packet has already left it, it can still retrieve the cached packet from its new neighbors. This is inspired by the work done in [10]. To allow for the identification of duplicate data packets, the source marks the data packets with a unique sequence number, and the destination keeps track of all the data packets seen.

D. Querying a Subset of Acquaintances

A node makes a lot of acquaintances over its life time. Hence, to reduce the control overhead it needs to limit the number of acquaintances it will *query* at any given time. However, a subset of its acquaintances has to be carefully chosen to cover all the Hubs it learned of from all its acquaintances.

Let H be a collection of subsets $\{H1, H2, ..., Hn\}$ of Hubs covered by the Hub lists of the acquaintances. Let C be the set of all the Hubs that a node learns of from all its acquaintances. Hence, $C = \bigcup\{H1, H2, ..., Hn\}$. Our problem is to find a minimum subset, $H' \subseteq H \;\; s.t.$:

$$\forall h \in C, \;\; \exists Hi \in H', \;\; s.t. \;\; h \in Hi$$

This is a minimum Set Cover problem and is known to be NP Complete [11]. To find an approximate solution, we have adopted the Quine-McCluskey optimization technique [12], [13] used widely in Boolean Algebra for minimization of boolean expressions. To describe this method, we define a few terms.

1) Prime Acquaintance: This acquaintance is not completely consumed by any other. That means, there is no other single acquaintance whose Hub list covers all of the Hubs in this node's Hub list. However, more than one other acquaintances may together cover all the Hubs in this node's Hub list. Formally, a node A with Hub list Hj would be a *Prime* acquaintance *iff*:

$$\nexists Hi, \;\; s.t. \;\; h \in Hj \Rightarrow h \in Hi, \;\; \forall h \in Hj$$

2) Essential Prime Acquaintance: This is a *Prime* acquaintance that covers at least one Hub that is not covered by any other *Prime* acquaintance. Let P be the set of all the *Prime* acquaintances. Then, a *Prime* acquaintance A with Hub list Hj would be an *Essential Prime* acquaintance *iff*:

$$\exists h \in Hj, \;\; s.t. \;\; h \notin Hi, \;\; \forall Hi \in P \; (i \neq j)$$

For example, if $A = \{1, 2\}, \; B = \{2, 3, 4\}, \; and \; C = \{1, 3\}$, then B or C alone cannot cover all the Hubs of A. So A is a *Prime* acquaintance. However, A does not cover any Hub that is not already covered by either B or C. So A is not an *Essential Prime* acquaintance. On the other hand, no single node covers all Hubs of B, and B covers Hub 4 that is not covered by anyone else. Thus, B is an *Essential Prime* acquaintance.

To query the optimal subset of acquaintances, a node first determines its *Prime* and *Essential Prime* acquaintances. All the *Essential Prime* acquaintances are chosen, and all the Hubs in C that they cover are marked. If any Hub is left unmarked, the non-essential *Prime* acquaintance covering the maximum number of unmarked Hubs is chosen and the corresponding Hubs are marked. This procedure is repeated with the remaining non-essential *Prime* acquaintances, until all the Hubs in C get marked.

E. Connection Maintenance

A session between a source and a destination becomes active when the first *data* packet is sent out from the source to the destination. This session expires when the inter-arrival time of any data packet in the same session exceeds a given threshold at the source. Once an active session is in place, the source puts its current Hub information along with its Hub list in each data packet. The destination reciprocates with similar information on getting the first data packet. From then onward, the source forwards data packets of the same session to the specified current Hub of the destination first, in order to reduce delay. Similarly, if the destination suffers an LAO or MAO Timeout, it notifies the source of the change by sending an *update* packet towards the current Hub of the source first. Such *update* packets are restricted between the two ends of an active session only.

VII. Mobility Impact on Protocol Performance

To study the effect of mobility on the performance of OBR, DSR and LAR1 (LAR in Scheme 1) we simulated each of the protocols with respect to all the mobility models suggested as examples in this paper, and compared the *data throughput*. For both DSR and LAR1, we borrowed the implementation available in GloMoSim. In our simulation of OBR, we fix the threshold for *logical hops* of *query* packets to 1. In this way, if the acquaintance of a source fails to provide the required information, it does not forward the *query* to its own acquaintances. As in Figure 12, OBR performs best for

Random Orbit and Uniform Orbit models as expected since the protocol was formed keeping the most general model in mind. The results for Restricted Orbit and Overlay Orbit are lower due to the restriction in movement imposed upon the mobile nodes that does not favor our acquaintance formation. In our modified Random Waypoint, all nodes have a single Hub as part of their LAO. So all the packets make their way to the center of the terrain irrespective of the destinations location, resulting in the worst performance. DSR on the other hand is seen in Figure 13 to perform the best with respect to the modified Random Waypoint where its flooding nature complements the fact that the nodes are evenly spread out all over the terrain. With respect to the other models it performs well with respect to the Random Orbit and Uniform Orbit for small number of Hubs when each Hub contains a fair share of the nodes, and does better for Restricted Orbit and Overlay Orbit when the number of Hubs increases, creating small Hubs with few nodes, thereby ensuring even node distribution. LAR1 (LAR in Scheme 1) as seen in Figure 14 is not much affected by the difference in mobility and performs consistently across all our example models.

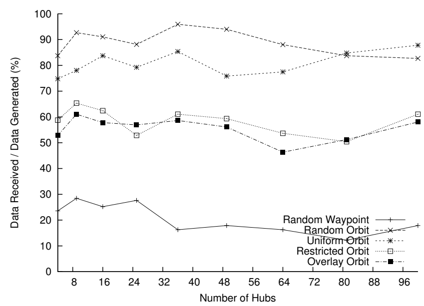

Fig. 12. OBR: Data Throughput vs. Number of Hubs

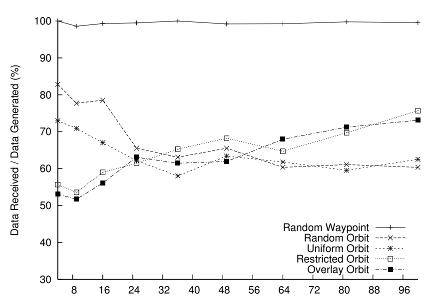

Fig. 13. DSR: Data Throughput vs. Number of Hubs

VIII. Numerical Study

In this section, we compare our proposed OBR protocol against DSR and LAR in Scheme 1 (LAR1). According to the discussion in the previous section, the overall data throughput of DSR was lower than OBR and LAR1, and reached a maximum when we considered around 10 Hubs in the Random Orbit model. Accordingly, we choose Random Orbit model with 10 Hubs to compare OBR against DSR and LAR1. We set up 150 random CBR connections, each sending ten packets with a 512 byte data payload. To assume realistic speeds we refer to the work done in [14], [15], [16], as summarized in Table II. Accordingly, we fix our LAO parameters (i.e. Hub Speed (min, max)) to 1 m/s and 10 m/s, and the MAO parameters (i.e. Node Speed (min, max)) to faster speeds of 10 m/s (23 mph) and 30 m/s (67 mph). We vary the two global attributes of our framework (i.e., *Hub Size* and *Hub Stay*) to study their effect on the *data throughput*, *control overhead* and *end-to-end delay* of OBR, DSR and LAR1. We use seven simulation runs with varying random seed values to plot each point in our results, which are as follows.

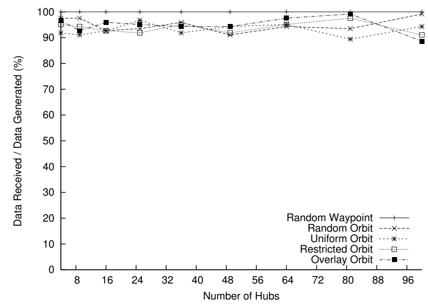

Fig. 14. LAR1: Data Throughput vs. Number of Hubs

TABLE II
Real Life Speed

Category	Type	Range
Walking	Average	$= 1.34\ m/s$
	Olympic Record	$\leq 4.02\ m/s$
Running	Average	$= 4.00\ m/s$
	Olympic Record	$< 10.00\ m/s$
Cycling	Average	$= 8.94\ m/s$
	Olympic Record	$< 13.89\ m/s$

A. Variation in Hub Size

The Hub size is significant on three fronts in the Random Orbit model. First, for a fixed radio range, a larger Hub means less coverage of each node in a Hub. Second, for a fixed terrain size, a change in the Hub size affects the amount of terrain covered by these Hubs. Third, it means increased overlap among the Hubs. In the following simulations, the Hubs were considered to be square regions with the common size of the sides being varied.

1) Data Throughput: The data throughput is measured in terms of the fraction of the total number of data packets generated that were received successfully. In OBR, a source learns of a destination by first making acquaintances with nodes that are within its radio range, and then using the distributed location database formed by the network of these acquaintances. Thus, the Hub size does not affect the data throughput of OBR, which is seen to be higher than that of both DSR and LAR1 in Figure 15. The repeated flooding of LAR1 aggressively locates the destination, but with increasing

Hub size the accuracy of the location estimation decreases, leading to decreasing data throughput. DSR suffers from loss of packets due to congestion at the MAC layer, as it tries to flood within small Hubs containing a lot of nodes (*broadcast storm problem*). With an increase in the Hub size, the performance of DSR steadily improves.

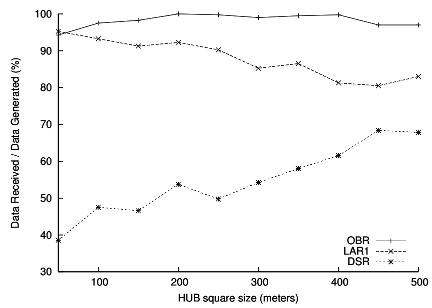

Fig. 15. Data Throughput vs. Hub Size

2) Control Overhead: The control overhead is measured in terms of the number of *hello, query, response* and *update* (if any) packets that are sent. LAR1 has the highest control overhead in Figure 16 by virtue of its repeated flooding nature, which becomes more acute with increasing Hub size that affects the location estimation accuracy, resulting in increasing overhead. In OBR, nodes periodically check for new neighbors to form new acquaintances. But, once an acquaintance is made, its information usually stays valid for a long time (due to a relatively large MAO value), leading to a much lower control overhead than LAR1 signifying higher energy efficiency. However, with increasing Hub size, the number of new neighbors increase, resulting in increasing overhead. DSR makes use of route cache and may end up flooding only once for a data packet with no cached route, thereby incurring the lowest control overhead.

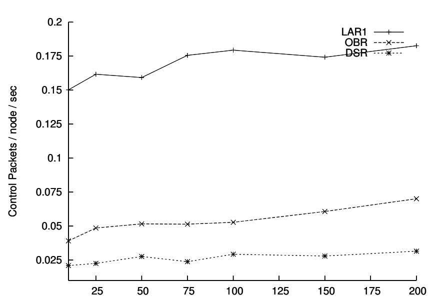

Fig. 16. Control Overhead vs. Hub Size

3) End-to-End Delay: The end-to-end delay is defined to be the time interval between the generation of a data packet at the source, and the reception of that data packet at the destination (including query and response delays, if they were required). As seen in Figure 17, DSR and LAR1 were not much affected by the change in the number of Hubs showing a delay to the order of 0.75 $millisecond$, while OBR showed marginally higher delay. More specifically, with increasing Hub size, when a packet enters a Hub it may have to take more hops towards the Hub center, resulting in the delay in OBR increasing from 1.5 to 2 $milliseconds$.

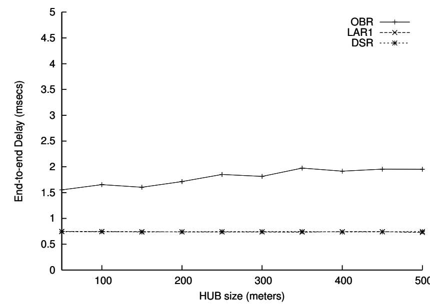

Fig. 17. End-to-End Delay vs. Hub Size

B. Variation in Hub Stay (LAO Timeout)

This parameter has a direct impact on the average node velocity. Lower LAO Timeout means shorter time spent by a node in a Hub, increasing the overall time spent in motion at higher MAO speeds. On the other hand, higher LAO Timeout signifies lesser nodes in transition between Hubs, thereby increasing the average node population in Hubs.

1) Data Throughput: Since nodes in OBR learn of a destination through the network of acquaintances, as long as there exists any mobility that expands this network and the distributed location database associated with it, OBR performs consistently well in terms of data throughput as seen in Figure 18. An increase in the LAO Timeout favors LAR1 by increasing its location estimation accuracy along with its data throughput. DSR suffers from congestion at the MAC layer as it tries to flood in a Hub with high node population. Thus, its data throughput steadily decreases with an increase in the LAO Timeout. Due to the random CBR traffic used by our simulations, DSR cannot effectively use cached routes to overcome this problem.

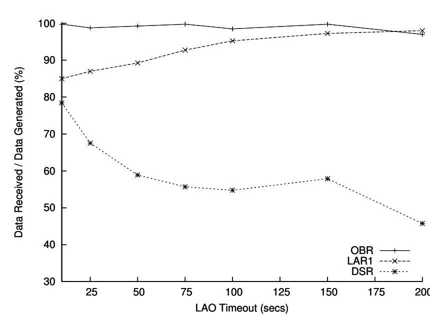

Fig. 18. Data Throughput vs. LAO Timeout

2) Control Overhead: The relative difference in control overhead shown in Figure 19 is similar to that seen in Figure 16 where LAR1 performs the worst, OBR performs much better, and DSR performs the best. However, in the face of decreasing mobility, LAR1 is able to make better location estimates resulting in decreasing overhead. Similarly in OBR, lower mobility reduces the number of new neighbors a node interacts with leading to marginally lower control overhead.

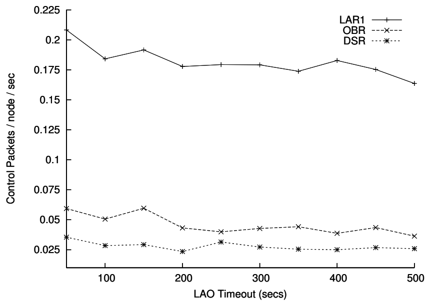

Fig. 19. Control Overhead vs. LAO Timeout

3) End-to-End Delay: As seen before in Figure 17, the delay in DSR and LAR1 is also seen in Figure 20 to remain unaffected at the order of 0.75 $millisecond$, while OBR showed marginally higher delay. More specifically, an increase in the LAO Timeout increases the probability of finding a destination in its last known current Hub, where a data packet is sent first (as described in Section VI-E), causing the delay to decrease from 2 to 1.5 $milliseconds$.

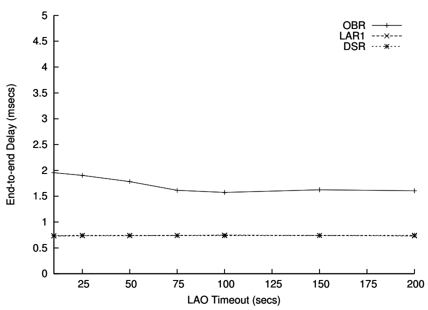

Fig. 20. End-to-End Delay vs. LAO Timeout

Although OBR seemed to have marginally higher delay than both DSR and LAR under the variation of both the global attributes, it is worth noting that this higher delay in OBR in the order of a few milliseconds, is far less significant as compared to the gains in data throughput (and control overhead) and hence may be deemed acceptable by most ad hoc network applications. Nevertheless, in future we intend to study the effect of either simulcasting packets to all the Hubs in a list, or multicasting them to a tree formed of the Hubs in the list, instead of sending to them sequentially in the hope of overcoming this excess delay.

IX. Comparison with Related Work

Random Waypoint is the most popular *Entity based* mobility model in literature. In [4], the authors studied an average speed decay problem in Random Waypoint and in [17], the author enhanced the model by using acceleration to smoothen changes in speed and direction. To account for obstacles, the authors in [18] proposed a mobility model based on voronoi graphs. In [19], the authors integrated three sub-models: perception, behavioral and movement, to simulate the mobility of each node individually as a close interaction of simple behavioral traits. In [20], the authors used *renewal theory* to guarantee a steady state in node movement distributions, while those in [21] introduced *stochastic correlation* in their VUM (variable user mobility) model for cellular systems. However, all these models focus on the mobility in a flat network.

In [22], [23], the authors first proposed a *Group based* mobility model called Reference Point Group Mobility, where an existing group leader determines a group's collective movement, while other members move independently within a small speed and angle deviation from that of the leader. Later they extended the mobility vector model into a framework, smoothening changes in speed and direction. In [24], the authors surveyed several *Entity based* (e.g., Boundless Area, Gauss-Markov) and *Group based* (e.g., Column, Nomadic, Pursue) mobility models for ad hoc networks. In [3], the authors proposed a framework for analyzing mobility models in terms of protocol independent metrics. They also suggested the *Manhattan* and *Freeway* models to suit city traffic. These models can all be incorporated within the ORBIT framework at different levels (see Figure 2) to generate more realistic models.

In [25], the authors suggested two hierarchical layers for a wireless ATM network: a deterministic Global Mobility Model to describe inter-cell movements, and a stochastic Local Mobility Model to describe intra-cell movements. In [26], the authors applied *transportation theory* to model: *City Area*, *Area Zone*, and *Street Unit*, at three hierarchical levels of detail. Similarly, the authors in [27] proposed the Metropolitan (*METMOD*), National (*NATMOD*) and International (*INTMOD*) mobility models to respectively suit movements within metropolitan areas, in between them and in between countries. Although the proposed ORBIT hierarchy closely resembles these hierarchies, our main contribution lies in the recognition of the 'orbital' pattern that exists around these hierarchies.

The authors in [28] proposed a framework for graph based modeling of mobility and traffic in large scale MANETs, while in [29], the authors developed a tool for modeling scenarios like *Airport, Highway, and Conference* using visualized user interface. ORBIT differs from these frameworks in its generality, by which it can integrate such tools within its black boxes at different levels to generate more practical models for real life scenarios.

In [30], [31], the authors analyzed existing MANET routing protocols based on suggested mobility models and scenarios, but did not propose any specific protocol to suit them. In [32], [33], the setup of a connected virtual backbone was suggested within MANETs to help routing protocols adapt to node mobility, while in [34], the authors applied link expiration prediction based on neighbor velocity information to several existing routing protocols. On the same note, the authors in [35] used an adaptive algorithm to predict mobility to help location tracking of mobile nodes. However, no prior work has been done to design routing schemes that take direct advantage of the overall underlying mobility, like our proposed OBR protocol, which leverages the ORBIT mobility framework to outperform other routing protocols like DSR and LAR1.

X. Conclusion

Appropriate modeling of node mobility in a MANET poses as the main challenge in evaluating protocol performance. To this end, literature has proposed several entity, group and scenario based mobility models. While some of them cater to short term networks (disasters, military, etc.), others model detailed scenarios. However, there is no model that captures the realistic orbital movement pattern found in our society.

In this work, we have proposed a novel framework called ORBIT that is practical, general and useful. More specifically, it identifies with sociological orbits, and is also able to integrate different mobility models into a single framework. We have analyzed models generated by ORBIT to exhibit wildly varying protocol independent metrics, proving its versatility in suiting different scenarios in both cellular and ad hoc wireless networks.

We have also designed an example Orbit Based Routing (OBR) protocol that is among the first to effectively leverage mobility information for routing packets in a MANET. OBR uses the underlying orbital mobility to determine a set of likely regions containing any node, and thus outperforms other protocols like DSR and LAR1. In short, our ORBIT framework is one of the most attractive candidates for modeling realistic mobility in various scenarios, and the principle of designing routing protocols based on mobility information is useful for many applications in wireless mobile networks.

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