

**The Importance of Mobility Model Assumptions on
Route Discovery, Data Delivery, and Route Maintenance
Protocols for *ad hoc* Mobile Networks**

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Introduction

The introduction of relatively low-cost mobile computing devices is having a profound impact on everyday life. Commerce and family life are both impacted by the ability to remain connected to other people and to exchange an ever increasing amount of information. Decisions, from setting up dinner dates to establishing geopolitical strategy, are being made using information processed by mobile computers and exchanged via wireless communication networks. People of all walks of life have discovered the power and freedom that networking, particularly wireless networking, affords. The ability to make more informed decisions faster is a central theme in the concept of Network Centric Warfare [Alberts 99].

Col John R. Boyd, USAF, (1927 – 1997) developed the concept of Observation - Orientation - Decision - Action (OODA) Loops, to model and describe a way of thinking about the use of information in the pursuit of goals. This concept has had a profound impact on the U.S. Department of Defense (most particularly, the U.S. Marine Corps); this impact has found its way into the popular culture and business. The phrase “get inside their OODA Loop” is synonymous with out-thinking and out-pacing an adversary. One of the key ingredients is information, provided better and faster, and with the aid of wireless networking technology, cheaper.

Much like the wired network must adapt to ever increasing demands in terms of users and content, the wireless network will experience tremendous growing pains over the next several years. Mobile devices will become more affordable and capable. While battery life will continue to be a significant limiting factor, displays will improve as will computation power and memory capacity. The operation of increasing numbers of devices forces us to think about ways to improve the utilization of scarce communications bandwidth.

Present mobile devices are synchronized with other computers using “cradles” – users crave the ability to synchronize “over the air”, eliminating the need for periodic resynchronization. This need, coupled with the increased use of these devices in mission-critical applications, highlights the need for research into robust transaction protocols for *ad hoc* mobile networks.

[Satyanarayanan] describes four specific constraints that affect mobile computing in general:

- Resource limitations. Processing capability, memory, and storage are limited. Because these devices can become lost or stolen, and because they can suffer catastrophic power failure, users require a data replication mechanism. Portability necessarily places an upper bound on the form factor, which limits the size of keys and displays. Designers have worked around the strict lower bound on input/output device size by developing styli for data entry, and magnification and scrolling to handle display issues.

- Hazards. Devices can be damaged by humidity, dust, dirt. More than a few mobile computers have suffered through drops on hard surfaces and down drains.
- Connectivity is expensive and tenuous. Unexpected termination (“re-dial opportunities”) are the norm, not the exception. Multi-path propagation and signal fading make communication difficult, if not impossible. Increasing demands on bandwidth, which is an inherently shared resource, makes achieving a guaranteed level of service difficult, but more important as these devices are increasingly used for mission-critical applications.
- Battery power means these devices have a finite energy source.

Additional constraints which arise from a close (and perhaps somewhat paranoid) reading of [Satyanarayanan] include:

- Meaconing. Can we trust location information that is provided to or by a mobile device?
- Intrusion. How do we determine if a device (or a communication channel) has been compromised?
- Jamming. Denial of service attacks are not a new phenomenon – it has been a staple of warfare since the dawn of electronic communication.
- Interference. Natural and synthetic noise places a limit on effective throughput – signal processing and power/aperture manipulation can help, but there is a natural limit to overcoming interference.

So far, we have discussed mobile computing devices in general. Mobile computers that are connected to fixed networks via cellular communications

capabilities can register for specific services, offload computing tasks to the fixed network, and rely on the fixed network for services such as location and routing. To find another device on the network, a user only need contact the mobile support station, and leave the rest of the computing to the fixed network. These general issues also apply to an emerging networking form: the *ad hoc* mobile network.

In *ad hoc* mobile networks, there is no fixed infrastructure. The client-server model is replaced by a peer-to-peer model. Networks are formed through discovery; mobile devices learn about their neighbors and communicate amongst themselves through a set of *ad hoc* networking protocols. Because this form of networking does not rely on the existence of fixed infrastructure, they are ideally suited for situations where such an infrastructure does not exist, or is unreliable. Examples include disaster relief and military operations.

Problem statement

Since *ad hoc* mobile devices learn about the network through discovery, and communicate with one another without the aid of a fixed network, we must have robust protocols to accomplish these tasks. Mobile devices must identify their neighbors, describe the services that they need and offer, and understand where other, specific mobile devices are logically (and perhaps physically) located within the network. Protocols to support mobile computing in general, and *ad hoc* mobile networks specifically, have been a hot research topic, which reflects growing demand and a realization that resource management (particularly bandwidth conservation) is essential.

Protocol development is necessarily a trade-off between robustness and economy. Protocols that are designed for very high levels of surety pay a significant price in efficiency. Forward error detection and correction is employed to overcome defects in the media. Acknowledgement protocols ensure that packets make it through the network safely. These methods individually add overhead to the communication process, reducing the portion of each message dedicated to “payload”, while ensuring a larger proportion of messages arrive at their destination. For *ad hoc* networking, we are particularly concerned about protocols that are used for route discovery, packet delivery, and route maintenance. Bandwidth that is used for route-related housekeeping is bandwidth not available for “payload”, so keeping this traffic to a minimum is an overt design goal.

Development and evaluation of mobile networking protocols requires some assumptions regarding the mobility and communication patterns of the mobile devices. Allocation of communication channels, caching of user location data, and support for location-aware applications are examples of network features that are sensitive to mobility and communication patterns. Good designs are a result of intelligent engineering trade-offs, so identifying representative mobility and communication patterns is essential to arriving at a robust design.

To establish relevance with a physical problem, it is necessary to understand the operational environment, the types of users whose behavior we are trying to model, and the types of behaviors they exhibit. We are concerned about applications where humans need to collaborate to accomplish a specific

mission, so some knowledge is required concerning the humans and the mission they are trying to accomplish. Figure 1 shows a picture of a typical operational environment for an *ad hoc* mobile network. In this specific example, users are interacting with one another through an *ad hoc* mobile network, and are supported by a fixed wireless network.

Table 2 briefly outlines the relationship between representative classes of users, their velocities, and the information they produce and consume. Velocity is not the only parameter that is critical, but it is the one most widely used in mobility modeling today. There are other, more useful parameters, such as acceleration and affinity that are equally relevant, but robust mobility models do not yet exist that allow easy incorporation of these parameters.

We must also understand the applications that will be facilitated with the mobile device. Mobile hosts will likely be running different applications concurrently. Applications have characteristic data input and output requirements, and frequently come with their own higher level protocols that enable these requirements. For instance, World Wide Web applications are associated with the HyperText Transfer Protocol (HTTP), while bulk data transfer is associated with the File Transfer Protocol (FTP). These protocols are suitable for wired networks; they are less suitable for wireless networks, where connectivity is more problematic and where costs are variable. To understand network performance, therefore, we must understand the applications that users expect to use, and craft the scenarios to reflect the nature of the data that is required to be carried by the network. Data characteristics such as connection

requirements, mean packet size, and “burstiness” must be defined to allow aggregate assessments in the models, and comparison with empirical data to support model validation. Different applications will have different needs, and perhaps different information delivery methods and topologies.

We can develop a taxonomy of applications – doing so may help understand the differences among these applications and to better understand the design trade space we have. In developing this taxonomy, we must also identify which information is delivery via a “pull”, which is a “push”, and which must be handled through a hybrid. Table 1 is a brief outline of an information delivery method taxonomy – putting more detail to this table will help shape the scenarios and inform the engineering trade-offs that must be made.

Information delivery method	Information type (example)	Update rate	Example Application
Push	Track states, Engagement orders, DON'T SHOOT ME ¹	Rapid	Cache invalidations
Pull	Weather, Tides	Low	WWW
Hybrid	Emerging threat information	Mixed	Information subscription

Table 1. Information Delivery Method Taxonomy

¹ One of the more useful information exchanges on the battlefield occurs immediately before a weapon is allocated – if the target area can be queried during the weapon-target pairing process, “friendlylies” can register their presence, reducing the incidence of fratricide.

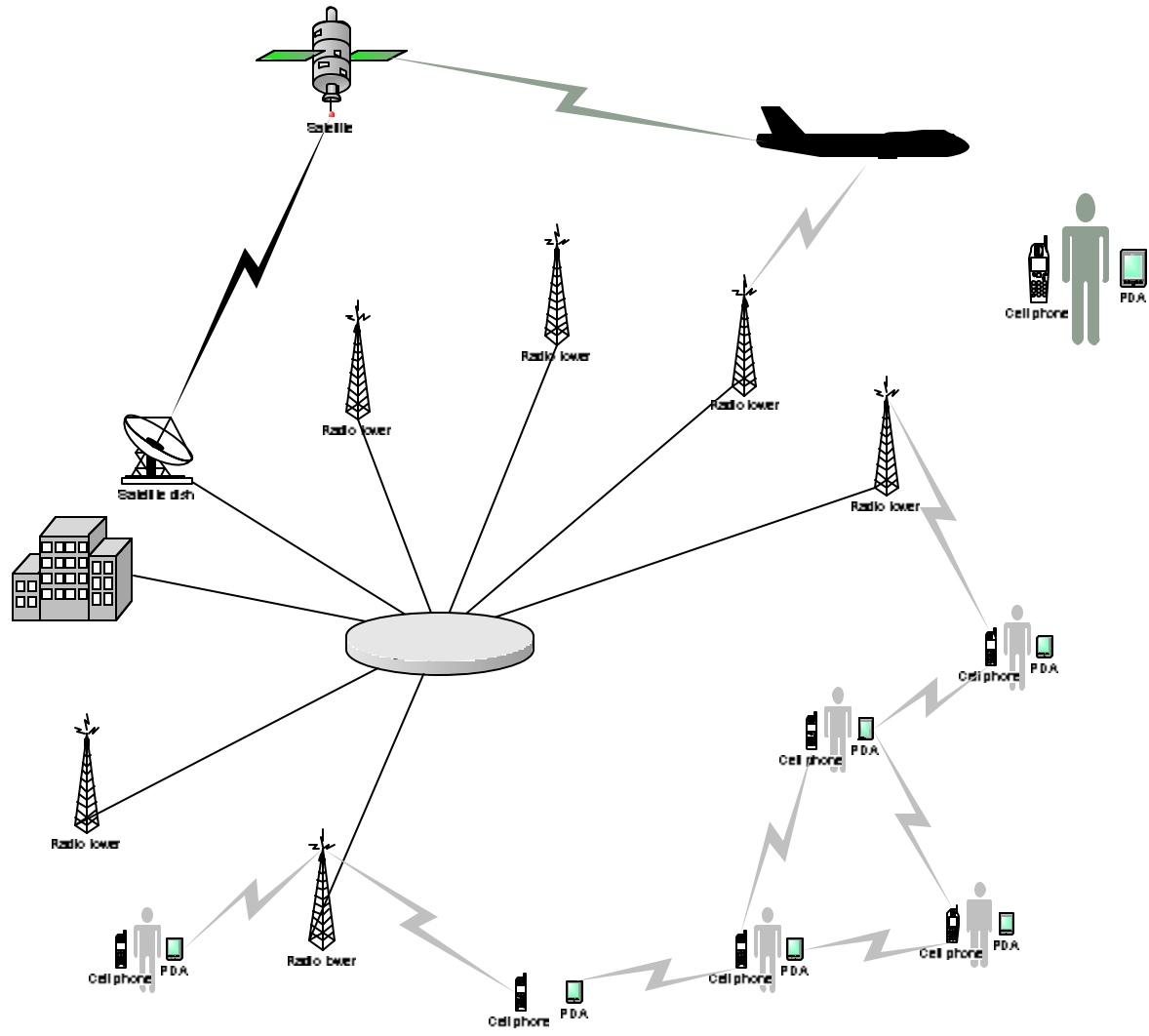


Figure 1. Operational View

Type	Example	Mean velocity	Data produced	Data consumed	Relative QoS
Sensor	(physiological monitors, seismic monitors)	0	Sensor measurements	Tasking/reprogramming	Low
Pedestrian	Dismounted Marine, soldier (battery power; RF network)	< 2 m/s		Simple data requests Small/simple transactions Primarily pull Data must be pruned/tailored Location-specific Sensor-poor Track states, engagement orders	Low
Motorcycle (e.g., KLR 250-D8)	Reconnaissance, Patrol	< 25 m/s		Primarily pull Small displays with specific HMI needs Data must be pruned/tailored Highly mobile (state range of mobility, both velocity and acceleration) Limited sensors Dependent upon others for SA information Track states	Low

Type	Example	Mean velocity	Data produced	Data consumed	Relative QoS
Light vehicle	HMMWV ² M998	< 25 m/s	PPLI ³	Track states, engagement orders	Medium
Armored vehicle	M1A1 Abrams	< 20 m/s	PPLI	Track states, engagement orders	Medium
Aircraft (fixed and rotary wing)	F/A-18E/F, F-35	< 300 m/s	PPLI, Track states, target video	Track states, target video	High
Ship	ARLEIGH BURKE Class Guided Missile Destroyer	< 15 m/s	PPLI, Track states, sensor measurements	PPLI, Track states, sensor measurements	High
Fixed site	Trucking company dispatcher Consumer service provider	0			

Table 2. User Characteristics

² High Mobility Multipurpose Wheeled Vehicle

³ Precise Participant Location and Identification – a GPS or network navigation-enhanced location report combined with positive network participant identification (provided by inference, based on encryption of the signal)

Given the set of applications and the scenario, we can objectively evaluate performance of the network, and can vary network parameters (such as protocol designs) to understand the sensitivity of ensemble performance to individual parameters. In Table 3, we show metrics for network performance. This table derives from U.S. Department of Defense Joint warfighting requirements related to the “picture” displayed to operators in support of theater-level air warfare operations, and shows the types of information that must be provided to operators via *ad hoc* mobile networks. While these are ensemble parameters, measurements are taken in each network participant’s track database (central track stores).

Attribute	Definition
Completeness	The air picture is complete when all objects are detected, tracked, and reported
Clarity	The air picture is clear when it does not include ambiguous or spurious tracks
Continuity	The air picture is continuous when the tracks are long lived and stable
Kinematical accuracy	The air picture is kinematically accurate when the position and velocity of a track agrees with the position and velocity of the associated target
ID Completeness	The ID is complete when all tracked objects are labeled in a state other than “unknown”
ID Accuracy	The ID is accurate when all tracked objects are labeled accurately
ID Clarity	The ID is ambiguous when a tracked object has two or more conflicting ID states
Commonality	The air picture is common when the tracks held by each participant have the same track number, position, and ID

Table 3. Single Integrated Air Picture Attributes

Our task is to identify a set of realistic scenarios that can be used to support system engineering efforts that will define network parameters. A

significant factor in these scenarios will be the mobility and communication pattern for individual and classes of users.

Previous work

There is a small set of scenarios that exist in the literature. [Hong 99] identifies several specific scenarios, and uses these to motivate the need for a group mobility model:

- Geographical partition (in-place mobility) – battlefield situation, where similar activities are undertaken in multiple areas simultaneously
- Overlap – different groups carry out different activities in the same area
- Convention – groups interact with their surroundings, as convention attendees interact with exhibitors

[Ho] describes three closely-related applications (scenarios); these applications vary in specific parameters, such as geographic area, number of participants, maximum velocity and acceleration, and minimum participant spacing:

- Art Gallery – similar to the convention scenario in [Hong 99], but with lower velocity and closer group spacing
- Event Hall – similar to the convention scenario in [Hong 99]
- Battle field – similar to art gallery and event hall, but with greater variation in velocity and inter-participant spacing

[Johansson] describes three “realistic” scenarios, within which nodes exhibit random behavior. Each node randomly selects waypoints in a square environment space (1 km x 1 km). At each waypoint, a node pauses for a

predefined time and selects the speed to the next waypoint from a uniformly distributed interval $[0..v_{max}]$. The three scenarios are:

- Conference – low mobility in obstructed environment
- Event coverage – fairly high mobility
- Disaster area – mixture of low and high mobility nodes

The variation of scenarios used in the literature highlights the need to settle on a set of common scenarios and assumptions that will support objective comparative analyses. Table 4 provides a short (and admittedly incomplete) list of parameters that must be specified to facilitate such analyses. It is important to have participants that behave in a normal way. Movement should be not only feasible (e.g., accelerations that do not cause failure of humans or machines), but realistic (e.g., high-g maneuvers of commercial aircraft are extremely uncommon, and usually result in departure from controlled flight).

Scenario parameters
Geographic area
Terrain
Cultural features
Number of participants
Participant types (assumes heterogeneous distribution)
Participant density (minimum, maximum, mean)
Participant distribution (including constraints)
Participant velocity (minimum, maximum, mean, median)
Participant acceleration (minimum, maximum, mean, median)
Participant radio effective radiated power and antenna pattern
Information exchange requirements (including type, periodicity)

Table 4. Representative Scenario Parameters

Within the scenarios are embedded assumptions about individual and group mobility. We are concerned with mobility models because mobility provides the central challenge in *ad hoc* mobile networks. If network participants did not

move, we could simply connect them with static networks, and treat them as wireless versions of wired networks. Because network participants move, the network must adapt to changing connectivity, and cannot rely on static (or slowly changing) routing protocols to deliver information.

Many papers have observed that *ad hoc* mobile network protocol performance is affected by the density, distribution, and motion of the mobile hosts. Several mobility models have been used in researching and evaluating *ad hoc* mobile computing protocols. There are two particularly good recent survey papers on the subject of *ad hoc* mobile network mobility models. [Hong 99] provides a good description of mobility models for both cellular network and *ad hoc* mobile network research. [Camp 01] expands on this work by providing additional examples and by providing a qualitative critique of selected models.

We must be concerned about the characteristics of these models, because network and application protocols are sensitive to route discovery and maintenance, which are sensitive to mobility patterns. These sensitivities affect performance of the network as a whole, and affect the ability to accomplish the mission assigned to a specific participant. Table 5 describes some of the individual mobility models in use today; Table 6 describes variations that account for group mobility.

Name	General Description	Representative behavior	Expression
Random walk mobility model [Zonoozi]	Each network participant moves in a random direction $[0, 2\pi]$ with random speed $[min, max]$	Erratic, memory-less motion	$r(t+1)=r(t)+r'$ where $r'=v \cdot t$ and v' is small and uniformly distributed in magnitude $[min, max]$ and direction $[0, 2\pi]$ [after Sanchez]
Modified random walk mobility model [Basagni]	Each network participant moves with random direction $[0, 2\pi]$ at constant speed	Erratic, memory-less motion	$r(t+1)=r(t)+r'$ where $r'=v \cdot t$ and v' is small and constant in magnitude and uniformly distributed in direction $[0, 2\pi]$
Modified random mobility model [Ko]	MH moves along a path comprised of several segments. Segment lengths are exponentially distributed random variables, and directions are random. Speed is uniformly distributed about a mean		
Random Waypoint mobility model [Johnson]	MH moves in repeated pause-and-move episodes. Destinations are randomly-chosen; speed is a uniformly-distributed random variable		
Mobility Vector model [Hong 01]	MH moves along trajectory described by base vector plus deviation vector	intended to produce smoother motion	Mobility vector $M = (x_m, y_m) = B + V$, where B = base vector and V = deviation vector.

Table 5. Representative *ad hoc* Mobile Networking Research Individual Mobility Models

Name	General Description	Representative behavior	Expression
Exponential Correlated Random (ECR) model [Bergamo]	Random group and individual motion		$b(t+1) = b(t)e^{\frac{-1}{t}} + \left(\mathbf{s} \sqrt{1 - \left(e^{\frac{-1}{t}} \right)^2} r \right)$ $b(t) = (r_t, \mathbf{q}_t)$ <p>t = rate of change adjustment r = random Gaussian variable with variance s</p>
Pursue and Nomadic Community models [Sanchez]	Pursue: individual motion in pursuit of group objective Nomadic Community: individual motion along hidden reference pattern	Target tracking (Pursue) and hunting/gathering (Nomadic Community)	Pursue: $r(t+1) = r(t) + a(t) + \text{random vector}$ Nomadic Community: $r(t+1) = r'(t+1) + \text{random vector}$
Reference Point Group Mobility [Hong 99]	Network participants are allocated to groups. Group motion is described by the motion of a centroid; individual motion within the group is random (uniform distribution)		

Table 6. Representative *ad hoc* Mobile Networking Research Group Mobility Models

For many of the reasons cited above, [Ho] asserts that the research community should arrive at a set of mobility patterns and calling patterns that allow objective assessment of competing proposals. [Ho] goes on to describe two approaches to arriving at a set of mobility and communication patterns that can be used in design and evaluation. First is the modeling of real world conditions; second is selecting a set of critical stressing performance criteria and focusing on measuring these. The first is more intuitive and is capable of being verified and validated against real world data. Additionally, a physical representation or interpretation of results is feasible with this approach. The second approach will focus on specific stressing conditions and may encourage point solutions. It is possible to use the first approach, while striving to explore the boundaries.

For the purpose of this paper, we recommend combining several features of the existing individual and group mobility models to explore the sensitivity of routing protocol performance to mobility patterns.

Proposed approach

Objects in the real world react to accelerations. The prevalent natural acceleration is that due to the force of gravity; every object near the surface of the earth is accelerated at 9.8 m/s in the direction of the center of mass of the earth. Moving objects also experience acceleration. We have convenient expressions for acceleration in several forms:

Acceleration in the tangential direction is given by $a_T = \frac{dw}{dt} r = \mathbf{a} r$, and acceleration in the radial direction is given by $a_R = \frac{v^2}{r} = \mathbf{w}^2 r$, where $\mathbf{a} = \frac{d\mathbf{w}}{dt}$ is the

instantaneous angular acceleration and ω = angular velocity. Cartesian coordinates are easier for most people to visualize; in rectilinear coordinates,

$$\mathbf{r} = i\mathbf{x} + j\mathbf{y} + k\mathbf{z}$$

$$\mathbf{v} = \frac{d\mathbf{r}}{dt} = i\mathbf{v}_x + j\mathbf{v}_y + k\mathbf{v}_z$$

$$\mathbf{a} = \frac{d\mathbf{v}}{dt} = i\mathbf{a}_x + j\mathbf{a}_y + k\mathbf{a}_z$$

The ideal approach would be to accurately model real-world entities using a physics-based, six-degrees-of-freedom mobility model, with realistic accelerations (thrust, drag, lift, gravity). Largely for reasons of computational complexity (motion is just one of many factors that must be calculated in the model), we simplify the equations of motion by using constant accelerations during each time interval.

The original hypothesis of this project was to combine features of the Random Group Mobility Model described in [Hong 99] with the Mobility Vector Model described in [Hong 01], and to use the resultant model to examine sensitivity of existing *ad hoc* routing protocols to changes in mobility generated by that model. The *ad hoc* mobile network model is GloMoSim [Bajaj][Zeng]. [Hong 99] proposes a Reference Point Group Mobility (RPGM) model, which establishes a reference point, or “logical center” for each group. Each node associated with that group has a location that moves along with the group reference point. [Hong 01] proposes a Mobility Vector Model that focuses on motion of a single participant.

We combine these models to achieve the benefits of both. The group reference points travel along a trajectory defined by an array of group velocities. For each interval of time, a group travels along a velocity vector. At the end of the

time period for which a specific velocity vector is valid, the next velocity vector is selected, and the process continues. When the list of velocity vectors is exhausted, the simulation ends.

At each time interval in the simulation, individual participant positions are calculated, and their velocity vectors are adjusted. Table 7 shows the calculations involved in this modified model.

Kinematical attribute	Group	Individual participant
Position	$\vec{r} = i x + j y + k z$	$\vec{r}_p = r + \mathbf{a} v$
Velocity	$\vec{v} = i v_x + j v_y + k v_z$	$\vec{v}_p = \mathbf{a} v$
Acceleration	$\vec{a} = c$	$\vec{a} = c$

Table 7. Modified Reference Group Mobility Model

This work was accomplished by developing a Java™ computer program that modeled the behavior of an arbitrary number of groups, each with an arbitrary number of participants. Each group was driven by a table containing velocities and the duration each velocity would be employed along the trajectory of the group. The reference point of each group was moved along this trajectory. Individual nodes within each group were driven along a trajectory based on the motion of the reference point, plus a perturbation vector. The magnitude of the perturbation vector was uniformly distributed over the range [0, reference point velocity], while the direction was normally distributed with a mean in the direction of group reference point motion. This computer program model was completed, and generated the desired input tables that were intended to be used with GloMoSim. Figure 2 is an example of the experiment set up possible with the mobility model, working with GloMoSim.

Number of groups	4
Number of nodes/group	4, 6, 4, 8
Group radius	100 m
Transmitter range	3 km
Receiver range	3 km
Simulation time	
Environment size	16 km x 16 km
Traffic type	Constant Bit Rate
Packet size	1024 bytes
Packet rate	1 Hz, 0.5 Hz, 0.2 Hz, 0.1 Hz
Number of transmitters	$0.5 * \text{Number of groups} * \text{Number of nodes/group}$

Figure 2. Experiment Design Parameters

Simulation results

Because of problems with the simulation, the original hypothesis could not be tested. The effort described by this paper was intended to exploit the mobility trace capability within GloMoSim. With the simple example provided with the simulation system, the system worked fine – with a more complete and realistic data set, the simulation failed to work correctly.

We do, however, demonstrate the sensitivity of routing protocol performance (AODV) to increases in mobility. Analytical or simulation studies and results obtained to validate the approach(es) proposed.

Simulation time	3600 s	
Terrain dimensions	2000 m x 2000 m	
Number of nodes	50, 100, 150, 200	
Node placement	Random	
Mobility model	Random Waypoint	
	Pause	30 s
	Min speed	0
	Max speed	10, 20, 30, 40
Protocol	AODV	
Data source	Constant Bit Rate	
Network protocol	IP	

Table 8. Simulation Parameters

Figure 3 shows the result of a series of GloMoSim runs using the parameters shown in Table 8. With the exception of the 100 participant run, the simulation output shows the expected decrease in throughput with increase in maximum participant velocity. This is due to the increased number of broken links due to increased average participant velocity.

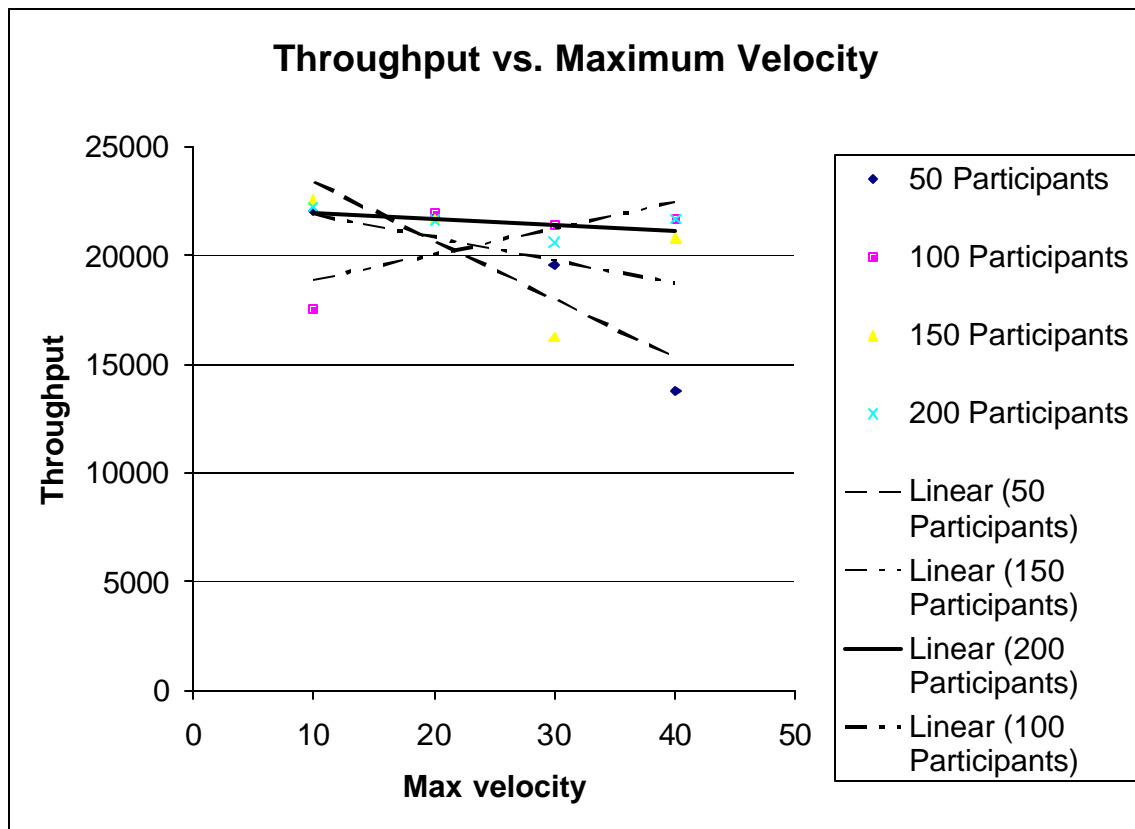


Figure 3. Throughput vs. Maximum Velocity

Future research opportunities

There is significant work left to be done in this area. For example, a set of reference scenarios should be constructed to permit objective assessment and comparative analyses. These scenarios should be validated against empirical data. Such validated scenarios would permit trade studies on protocol designs.

An important part of these scenarios is the mobility model. A standard mobility model should be developed for ad hoc mobile networks for the same reasons we need standard scenarios. Routing protocols are very sensitive to participant mobility, so using realistic models is critical to obtaining credible results. Specific actions include:

- Develop a family of mobility models that can be used to compare performance of algorithms at every level of the protocol stack (e.g., MAC, network, transport, application).
- Perform verification and validation on those models against field trial data. Conduct experiments to obtain information to understand which of these mobility models best represent real world behavior.
- The models used to predict radio-frequency propagation do not account for propagation problems due to topography, vegetation, or cultural features. It is relatively easy to add topography to these models, as this data is readily available. Adding vegetation and cultural features is much more difficult, as the data is not readily available and has a relatively small time constant.
- The GloMoSim mobility trace function must be debugged to understand its behavior and to correct the defect observed during this research effort. Additional work is also required to build a graphical user interface for the mobility model and to integrate it with GloMoSim. Modifications are also needed in the GloMoSim user interface to improve usability.

- Modify the computer program developed for this project to model a variety of mobility patterns – let users decide the parameters, then generate the mobility trace file to run with the corrected GloMoSim model. Also, enhance the mobility model program to model behavior exhibited by boids [Ho].

Conclusions

While we were not able to test the original hypothesis, we were able to complete the framework of a mobility model that can be extended to a more general case. We were able to experiment with GloMoSim to understand its capabilities and limitations, and to begin to explore routing protocol sensitivities to participant motion.

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