

# TriM: Tri-Modal Data Communication in Mobile Ad-Hoc Networks<sup>1</sup>

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**Abstract.** A Mobile Ad-Hoc Network (MANET) is a group of wireless, mobile, battery-powered clients and servers that autonomously form temporary networks. Three data communication modes can be provided in a MANET, data broadcast, data query, and peer-to-peer messaging. Currently, no MANET data communication protocol provides the ability to use all MANET data communication modes. The objective of this research is to develop a MANET data communication protocol, TriM (for Tri-Modal communication), capable of providing all three data communication methods. TriM was designed to accommodate node disconnection and reconnection through periodic synchronization. Each part of the protocol has minimum power consumption as a goal. Simulation showed TriM minimizes the average power consumption of servers and clients while accommodating node disconnection.

## 1 Introduction

A MANET is a collection of mobile, wireless and battery powered servers and clients [5]. The topology of a MANET changes frequently as nodes move. A MANET is a potential solution whenever a temporary network is needed and no fixed infrastructure exists. MANETs differ from traditional mobile networks. In traditional mobile networks the servers, and potentially some clients, are stationary and powered by a fixed power grid. The servers communicate with the mobile clients over a wireless link. A MANET provides the traditional wireless network capabilities of data push and data pull as well as allowing clients to communicate directly in peer-to-peer communication without the use of a server, unless necessary for routing [1]. Due to servers having a larger capacity than clients [5], we assume that servers contain the complete database management system (DBMS) and bear the responsibility for data broadcast and satisfying client queries.

Nodes (clients and servers) may not remain connected to the MANET throughout their life. To be connected to the network, a node must be able to hear the transmission of at least one other node on the network and have sufficient power to function. We assume a fixed transmission power level. Network nodes (clients and servers)

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may operate in any of the three modes that are designed to facilitate the reduction in power used [8]. These are: **transmit** – this mode uses the most power, allowing transmission and reception of messages, **receive** – this mode allows the processing of data and reception of transmissions, and **standby** – in this mode, the CPU does no processing, transmitting or receiving.

Traditional mobile network research must address the limitations of the wireless bandwidth as well as the mobility and battery power of clients. MANET must consider these issues for both clients and servers. This prevents the use of current traditional mobile network data communication protocols, which assume stationary servers with unlimited power.

The majority of research in MANET has centered on routing issues [1][7]. Over the past few years, interest in data communication has been increasing [5][16][17]. However, current MANET data communications protocols have provided only one or two modes of data communication. Unlike TriM, no current protocol provides the ability for a MANET to use all three modes of data communication.

The rest of this paper is organized as follows. Section 2 will present the current research in MANET data communication. In Section 3 TriM, a MANET data communication protocol allowing all three modes of data communication is proposed. Section 4 describes the scenarios simulated and the results of the simulations for the TriM protocol. Section 5 provides conclusions and outlines future work.

## 2 Current MANET Data Communication Research

The data communication research issues in MANET center around two areas. These issues are covered in detail in [3][4]. The first area concerns the limitations of the environment (wireless, limited bandwidth, battery powered, mobile) for both clients and servers. The second area concerns the three ways in which MANET data communication may take place. Within this area, concerns due to data push, data pull and peer-to-peer communications exist.

Some work in MANET data communication has been scenario specific. In the work of Jung [9], location dependent queries in urban areas are addressed. Tang [13] adapts MANET data broadcasting to power controlled wireless ad-hoc networks. In these networks, servers have the ability to broadcast at one of several discrete power levels. The work of Tseng [14] deals with the broadcast storm.

Wieselthier, et al, have been working on MANET data broadcast. Their approach is the construction of a minimum-energy tree rooted at the broadcast source [15][16]. Two algorithms, one for broadcast and one for multicast were described.[15]. The algorithms were tested and showed that by utilizing broadcast in a mobile environment, energy savings can be achieved. However, the networks tested were small and node mobility was not addressed. The cost of building the tree is considered negligible by the authors [15]. However, it has been shown that tree-based protocols do poorly when there is node mobility [6] The problems of limited bandwidth, the need for tree maintenance, and node mobility also remain.

Two protocols to handle data push and data pull within the MANET were proposed by Gruenwald, et al. [5]. They use a global network where all servers in a region

know the location and power of all other servers in the region and full replication of the database is assumed. Periodically, each server broadcasts its location and power level. This begins the broadcast cycle [5]. Data deadlines are used to determine which data requests to service. The protocols include a leader selection protocol. The leader coordinates the broadcast responsibilities of other servers in its region by determining which portion of the broadcast each server transmits. No server transmits the entire broadcast unless it is the only server in a region. Between broadcast transmissions, clients are permitted to query the servers [5]. These algorithms have a potentially large overhead as mobility may cause the leader selection protocol to run frequently. While selecting a leader, less popular items may starve or be broadcast too late [5]. In addition, servers with no clients still broadcast, wasting power.

The second protocol includes the use of a popularity factor (PF), as suggested by Datta [2]. The PF is a measure of the importance of a data item. The PF increases each time a request is made for a data item [5]. An additional factor, Resident Latency (RL) also affects the PF. If it has been too long, the need to broadcast the item may be gone. RL is system and scenario specific [5]. The PF decreases whenever request age exceeds the RL [5]. If a server has not received any requests for a certain number of broadcasts, it will sleep rather than broadcast to an empty audience [5]. Finally, to localize data delivery, the lead server assigns each server the amount of data to broadcast but not which items [5]. In addition to leader selection costs, calculation of the PF and comparison to the RL add to the overhead, further delaying data delivery.

### 3 TriM Data Communication Protocol

In the following subsections, the TriM data communication protocol is presented. The specific parameters used to control the protocol are not listed but are available in [4]. This paper describes the overall design of TriM. In Figure 1 we see an overview of TriM. This figure shows a single iteration. The protocol will cycle through these stages repeatedly. A single time through these stages is referred to as a service cycle (SC). Here we see the relationship of each data communication mode within the protocol. Prior to the first iteration of the SC, the network is initialized. At this time, all protocol parameters are set. Currently, these parameters are static.

<b>Synchronization Stage</b>	<b>Data Push Stage</b> Data Broadcast	<b>Data Pull Stage</b> Data Request Peer-to-Peer	<b>Idle Stage</b>
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Fig. 1. TriM Data Communication Protocol

In two of the four stages, data communication can take place. These are the data push stage and the data pull stage. The synchronization stage allows servers/clients to synchronize and detect the other nodes in their immediate vicinity. The idle stage allows the setting of a period of time during which all nodes are inactive. This gives the network designer the ability to set the frequency of data communication within the network. By setting this parameter carefully, we can avoid too frequent repetition of

broadcasts or the other energy expensive portions of data communication. The service cycle repeats until the network is taken out of service or all nodes fail.

### **3.1 Network Initialization and Control**

There are four stages, synchronization, data push, data pull and idle, in TriM. The first three are active while the last one is inactive. Within each active stage there are tasks associated with the servers and tasks associated with the clients.

Network initialization is accomplished when deploying a MANET. The network designer determines the length of each of the network stages according to the needs of the network and the characteristics of that particular deployment. Network initialization involves a variety of parameters. Each node in the network (server and client) is initialized using the same parameter values. These values are static throughout the MANET deployment. The database maintained by the servers is assumed to be fully replicated. Each server and client independently monitors its location in the SC based on these common parameters and uses them for synchronization with other nodes.

### **3.2 TriM Synchronization Stage**

The synchronization stage has two parts. The first part is restricted to the transmission of information by servers (LMHs). Servers transmit their unique ID and location. This information is necessary to perform peer-to-peer message routing and is used by clients (SMHs) during data query to select the nearest LMH to query. There are generally fewer LMHs and their individual presence is critical to the protocol. Sufficient time is allocated during LMH synchronization to allow all LMHs to transmit their information independently. Each LMH knows the number of LMHs that were deployed during network initialization. The unique IDs are numbered from 1 to  $n$ . Each LMH transmits its information in turn, waiting the appropriate period of time before transmitting its information. The importance of the LMH information to the protocol prohibits transmission in parallel. Collisions in the limited bandwidth of wireless networks could cause the loss of critical information from neighboring LMHs. The amount of time a LMH must wait is determined by the number of LMHs having smaller IDs and the time needed for it to transmit its ID and location.

The second stage is for transmission of information by clients (SMHs). Each SMH transmits their unique ID and location. To perform routing of peer-to-peer messages during the data pull stage, the location of each SMH is needed. However, the number of SMHs is potentially large and it may not be possible to reserve sufficient time for each SMH to transmit independently. SMHs transmit their information when the transmission channel is clear. SMH location information is updated when synchronization provides new information; otherwise the most recent data available is used.

The synchronization stage is important as it synchronizes all nodes in the MANET. By regularly synchronizing all nodes, each node will be in the same protocol stage at the same time. This prevents contention over the limited network bandwidth. This is especially important during data broadcast, which immediately follows synchronization. The results of synchronization also play a role in data query and peer-to-peer

communication. The synchronization stage occurs once per SC. During synchronization, nodes can determine if they are currently disconnected from the network. If a node detects no other nodes during synchronization, it will sleep until the next service cycle.

### 3.3 TriM Data Push Stage

The second stage of the service cycle is the data push or broadcast stage. The data push stage occurs before data pull so that the maximum number of potential data needs can be served before a server becomes too weak to transmit data. Separating data push and data pull reduces the contention for the limited bandwidth. When the data needs of a client are satisfied by the broadcast, the need for data query is eliminated. This results in a power savings.

**Servers – Data Push Stage** The autonomous and mobile nature of this self-organizing network suggests independent LMHs. This eliminates the need for and energy consumption of a leader selection protocol. The decision of whether to transmit a data broadcast is a local one, made by each server. The contents of the broadcast are also partially determined by each server. The data broadcast will be composed of both a pre-selected set of data items and a set of dynamically selected items. The pre-selected items are determined at MANET deployment by the network designer. These are data items that each client needs frequently. The fixed portion of the broadcast is the same for each LMH. The dynamic portion of the data broadcast will vary, depending on the unserved data queries of the SMHs within transmission range of each LMH during the previous service cycle.

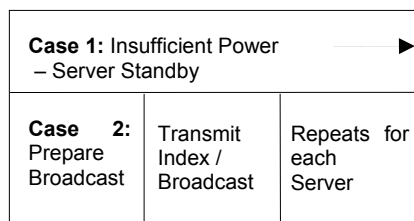


Fig. 2. TriM Data Push Stage – Server

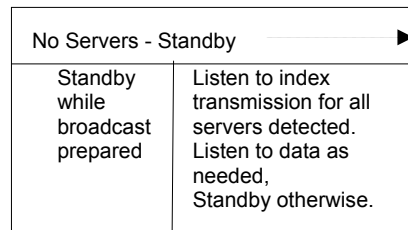


Fig. 3. TriM Data Push Stage - Client

Figure 2 shows the broadcast portion of the service cycle for servers. Two possible situations are shown. In the first situation, the server has insufficient power to transmit an index and data broadcast. The LMH will go into standby mode. In the other case, the index and broadcast are transmitted in server ID order with each server being allocated a broadcast slot to prevent collision. As the size of the MANET broadcast is meant to be of minimal size, a single transmission of the index is preferred as transmission of the index takes time and consumes power. Servers do not listen to the broadcast transmissions of other servers. As several servers may broadcast in the same region, duplication of the broadcast static portion is a waste of power. To some extent, this cannot be prevented. A client may be in the transmission range of several or only one of the servers, depending on its geographic location.

**Clients – Data Push Stage** Clients, like servers, have two potential situations during data push. If a client detects no servers during synchronization, it will be in standby. The client behavior is shown in Figure 3. Each SMH knows from the synchronization stage which LMHs will transmit in their region. The SMHs can then tune into receivable transmissions. The SMH will receive the static portion from any of the LMH transmissions it receives, but need only listen to the static portion once. A SMH will also check the index for any needed dynamic data items. It will use the index to determine when the data item will be transmitted. The index contains a list of all data items that will be transmitted as a part of the broadcast, and the order in which they will be transmitted. A SMH needs only listen to transmitted indices, the static data portion once and dynamic data items of interest. To listen to these items, the SMH must be in receive mode. The remainder of the time, the SMH may be in sleep mode.

### 3.4 TriM Data Pull Stage

During the data pull stage, both data query and peer-to-peer communication occur. During data query, servers respond to data requests from clients. A server may also be asked to do routing of peer-to-peer communications. In data query, clients request data from servers when the data they need was not in the recent broadcast. In peer-to-peer communication, clients communicate directly with other clients. Selection of peer-to-peer communication partners is determined by the application rather than TriM. If the client contacted is disconnected from the network, the message is dropped. During data pull, all nodes are aware that their transmission may not be heard as nodes detected during synchronization may now be out of transmission range. For this reason, clients will not retransmit the same query or peer message twice during the data pull stage in a single service cycle.

**Servers – Data Pull Stage** The actions of servers during the data pull stage of the service cycle are shown in Figure 4. The servers have two primary tasks during the data pull stage. First they must respond to data queries. Any data query that is not serviced during this data pull stage is added to the dynamic data portion of the broadcast in the next service cycle. Second, servers must route client peer communications when requested.

Do the following in any order, as necessary:

- Perform any LMH communication
- Transmit any routing requests
- Process and transmit data requests

Switch to Transmit Mode whenever transmitting a query reply or routing a message; Receive Mode otherwise

**Fig. 4.** Trim Data Pull Stage – Server

Transmit while transmitting queries to LMHs or responses to SMHs.

Receive while generating queries, receiving results of query from LMH or messages from other SMHs

When not busy, Receive.

**Fig. 5.** TriM Data Pull Stage – Client

**Clients – Data Pull Stage** A SMH has only a few potential tasks during data pull as shown in Figure 5. The first situation is when a client needs to make a data request.

The client will be in transmit mode while transmitting the data query and will be in receive mode as it awaits a response. Second, a client may need to communicate directly with another client. If the target client is detected during the most recent synchronization stage, it will transmit to the target directly. Otherwise, a routing request will be sent to a server. Finally, a client may receive a peer message. If this occurs, the receiving client will create a reply, change to transmit mode and transmit the reply.

### **3.5 TriM Idle Stage**

Following the data pull stage a MANET will enter into a period where all nodes are in standby. The length of this period is determined by the network designer and is set at network deployment. Standby uses very little power. This period is determined by the necessary frequency of broadcasts for the network to perform its designed functions. Following the idle stage, the service cycle will repeat.

## **4 Simulation of TriM**

In order to test the TriM protocol, a variety of scenarios were simulated. The AweSim simulation software [12] using inserts coded in the C programming language to describe network behavior was used for this simulation study. AweSim is a general-purpose simulation tool that provides discrete event simulation of user defined networks [11]. The deployment of a MANET and the execution of the proposed MANET data communication protocol can be defined as a set of discrete events that occur during the operation of the protocol. These events are network deployment and initialization, repeated execution of the MANET data communication service cycle (SC), and a network report event that executes once at the conclusion of network simulation. In order to compare TriM to the Leader Selection protocol [5] simulations are performed with values matching those used in that study. Additional scenarios were run using as a guideline the parameters used in [9][10][13][14].

The simulation runs vary data push parameters and data pull parameters. Three data broadcast sizes (50, 100 and 200 items) are simulated for each of the data pull settings. These broadcast sizes are referred to in the results as small, medium and large broadcasts, respectively. The data pull parameters are the frequency of data query and peer messaging. Data query and peer messaging are set to the same value. As both data query and peer message frequency are set to the same value, they are referred to collectively as pull frequency throughout this paper. The values used for pull frequency are 5, 20 and 40 items/sec. These are referred to as low, medium and high pull frequency, respectively. This variation simulates different loads on the network. This results in nine different workloads for each of the three scenarios. Each of the nine workloads was simulated 10 times. Table 1 shows other parameters used in the simulation. The simulations assume that the LMHs and SMHs are initialized in random locations throughout the roaming region. Once the network is initialized, motion of all nodes is random with respect to speed and direction. However, the random speed must be within the mobility range and roaming region specified.

**Table 1.** Parameters for MANET Data Communication Simulation

Parameter	Value	Parameter	Value
Bandwidth LMH SMH	2 Mbps 100 Kbps	LMH Power Dissipation Transmit Mode Receive Mode Standby Mode	170 w 20 w 2 w
Communication Radius LMH SMH	250 meters 100 meters	SMH Power Dissipation Transmit Mode Receive Mode Standby Mode	7 w 1 w 0.1 w
CPU Power LMH SMH	1700 MIPS 100 MIPS	Mobility – all nodes	0 to 1 m/sec
Number of Nodes LMH SMH	6 1000	Size of roaming region Simulation Time	1 km x 1 km 1 hour

As with any simulation, some assumptions must be made. During the SMH portion of synchronization, the average number of SMHs within reach of each LMH must be calculated. As the nodes are distributed randomly in the region, the average used is *number of SMH / number of LMH*. The next stage is the data push stage. In this stage, a broadcast is built. It is assumed that each broadcast transmission is equally split between static and dynamic data items. This means that a broadcast is always at least half full. It is further assumed that a SMH listens to the static portion of one broadcast transmission and to the entire dynamic portion of each broadcast transmission in its region. In data pull we assume a static number of data queries and peer messages per node. The values used in the simulation are request frequencies of 5, 20 and 40 queries/messages per second. During simulation, the distance between nodes is calculated and compared to benchmark transmission ranges to determine if a SMH can hear a LMH and if a SMH transmission can reach other nodes. It is assumed that a SMH will send all data queries and routing requests to the closest LMH detected during synchronization if it is within SMH transmission range.

#### 4.1 Evaluation Criteria

- **Average Power Consumption** The average power consumed by clients and the average power consumed by servers are calculated. For each client and server the power consumed per time unit is calculated by multiplying the percentage of time a node spends in each mode by the cost in power dissipation of each power mode.
- **Percentage of Coverage** The effect of mobility that we measure is the percentage of SMHs out of range of all data broadcast transmissions. This demonstrates the effect of network mobility and implies the level of node disconnection in the network.
- **Broadcast Effectiveness** The broadcast portion of the MANET is important, as data push is energy efficient. The measure for this portion of data communication will be broadcast effectiveness, which is the ratio of items of interest in a broadcast to the total number of items transmitted.



- **Query Efficiency** The data pull section will rely on the measurement of query efficiency. This is a measure of the percentage of data queries that get served during an entire simulation.
- **Peer Efficiency** Peer-to-peer communication is a time when clients can communicate directly with clients. Peer efficiency is measured as a percentage of the messages sent to peers by the number of messages received by peers.

## 4.2 Simulation Results

The initial scenario simulated was a comparison between the Leader Selection protocol [5] and TriM. The Leader Selection protocol is a soft real-time MANET data broadcast protocol. Data query, as described in this paper does not exist. Rather, data requests help inform the building of subsequent data broadcasts. Individual data items are not served interactively and no peer-to-peer communication occurs. This protocol is selected for comparison to TriM as it is one of the few MANET data communication algorithms that allow multiple data communication methods while providing sufficient data for comparison. This protocol provides 4 measures for evaluation, which are energy consumed by LMHs, energy consumed by SMHs, access time and broadcast hit ratio. A complete comparison cannot be made due to protocol differences. However a partial comparison is possible.

Energy consumption is measured for both LMHs and SMHs in both protocols. In Leader Selection, 6 variations of the protocol were tested, providing the range of values shown in Table 2. In addition, our Broadcast Effectiveness (BE) is similar to the Broadcast Hit Ratio (BHR) of [5] when the probability that dynamic items in the broadcast are of interest is 1. To make the comparison as accurate as possible, the simulation used as many of the parameters of [5] as possible, including number of SMHs and LMHs, CPU power, bandwidth, and transmission radius, size of simulation region and database size. Each LMH transmitted 20% of the database in each data broadcast. Table 2 shows the comparison between Leader Selection and TriM. Peer Efficiency and Query Efficiency were not calculated, as they have no corresponding value in [5].

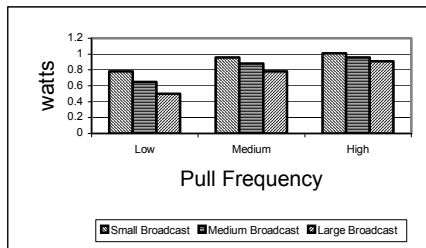
**Table 2.** TriM Comparison to Leader Selection Protocol

	<b>TriM</b>	<b>Leader Selection</b>
SMH Avg Power Consumption (watts)	0.19	20-60
LMH Avg Power Consumption (watts)	18.99	15-24
Percent SMH Hearing Broadcast	95.9	Not applicable
Broadcast Effectiveness/Broadcast Hit Ratio	70.36 BE	60-100 BHR

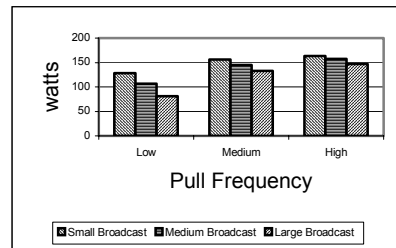
The behavior of TriM was similar to the Leader Selection protocol. The major departure is in the SMH power consumption. This is due to a difference in how SMHs are used in the two protocols. In Leader Selection, SMHs drive the contents of the data broadcast. In TriM, the SMHs only request what was not received in a recent data broadcast. The primary advantage of TriM over Leader Selection is the addition of peer messaging and interactive data query, which are not available in Leader Selection. TriM compares favorably with Leader Selection.

The remainder of the data presented is for the 9 workloads described above. It

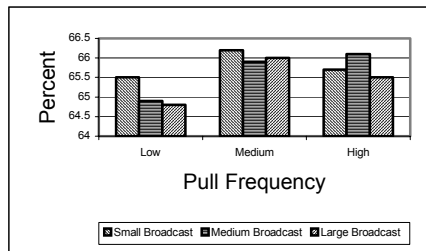
should be noted that when a LMH must choose between routing peer messages and serving data queries, routing takes precedence. The rationale is that data queries can be added to the next data broadcast while peer messages are dropped at the end of data pull. Figure 6 shows the average client power consumption simulation results for all 9 variations of broadcast size and pull frequency. Figures 7, 8, 9, 10, and 11 show the average LMH power consumption and the percentage of SMHs hearing a broadcast, Broadcast Effectiveness, Query Effectiveness and Peer Effectiveness, respectively.



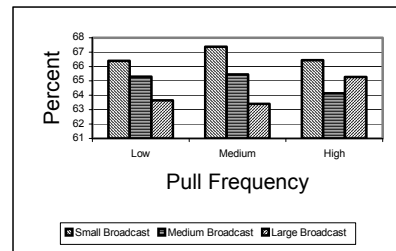
**Fig. 6.** Avg. Client Power Consumption



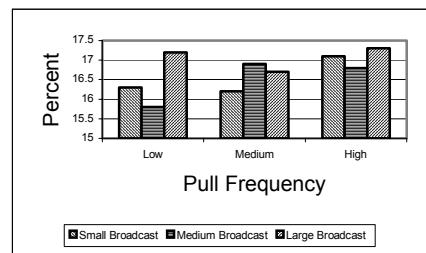
**Fig. 7.** Avg. Server Power Consumption



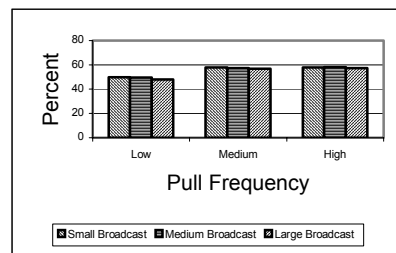
**Fig. 8.** % of SMHs hearing Data Broadcast



**Fig. 9.** Broadcast Effectiveness



**Fig. 10.** Query Efficiency



**Fig. 11.** Peer Efficiency

To understand the results, it is important to know that the length of each stage of the service cycle changes from one workload to the next. For instance, as the maximum size of the data broadcast increases, so does the length of the data push stage. When the pull frequency increases, the data push stage is also increased in length. As the length of the service cycle increases because of a larger data broadcast, the average power consumption for LMH decreases as less time is spent transmitting. While each broadcast transmission is longer, the amount of time waiting for the other LMHs to transmit also increases. As the length of a service cycle increases due to a larger

pull frequency, the average power consumption increases due to the increase of transmission by each LMH. A larger pull frequency requires a greater number of data queries to be processed per second.

The average power consumption for SMHs is nearly at the receive level. Nearly two thirds of the SMHs were within the reach of a LMH transmission. The broadcast effectiveness suffered as a SMH was more likely to be within range of more than 1 LMH. The static portion of the broadcast transmission is then duplicative and lowers broadcast effectiveness. While effectiveness is lower, most clients are served. In this scenario the level of disconnection in the MANET is low as a large number of nodes occupy a small space. In fact, the 6 LMHs serve a population of 1000 SMHs. Because of this, the amount of time spent in data pull is much higher than the time spent in data push. Data pull is more expensive as each LMH responds to individual queries and routing requests. During data pull, LMHs serving a large number of SMHs may spend the majority of their time in transmit mode.

Query efficiency is rather low. This can be accounted for in two ways. First, less than two thirds of the SMHs can make a data request. While two thirds heard a broadcast, the transmission range of a SMH is less than half of the transmission range of a LMH. Second, the large number of SMH served by each of the very few LMHs will be high.

Perhaps the most interesting result from the simulation is the consistency of results, regardless of broadcast size or query/peer frequencies.

## **5 Conclusions and Future Work**

This paper presented a protocol that allows all three forms of MANET data communication, preserving power and accommodating limited bandwidth and mobility. The proposed protocol, TriM, compared favorably to the Leader Selection MANET data communication protocol while providing the additional capability of peer-to-peer messaging. In the scenarios simulated, data query and peer messaging were reasonably successful and TriM performed well in simulation.

The development of additional MANET scenarios is needed. Some MANET applications suggested in the literature have parameters different from those used. Included in future work is the development of appropriate mobility models. When the movement characteristics of nodes within the scenario are better parameterized, it may be found that current protocols need additional modification. In addition to mobility models, the effect of increased transmission ranges should be investigated. The ability to increase coverage through data relay and greater node cooperation should be studied. Currently, no standard method exists for the study and evaluation of MANET data communication protocols. The development and acceptance of a standard benchmark is recommended. Further work on the protocol itself is in order. Adding real-time capabilities, directional antennas, variable power transmissions, etc. provide a list of items that can be added to a new or modified protocol.

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