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Assessing Tradeoffs in Mobile Ad-Hoc Network Deployment: A Case Study in Ground Soldier Mobile Systems

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14. ABSTRACT

This study examines performance tradeoffs in the deployment of EPLRS networks with emphasis on the impact of radio density. We formulate three models of network operation and exercise these models under various deployment scenarios. Our findings indicate that while increasing radio density need not have a significant detrimental impact on network performance, it can pose additional challenges from a network management perspective.

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ABSTRACT

Advances in information technology are yielding dramatic changes in the use of real-time information sharing to support military operations in complex environments. As the military use of wireless devices and services continues to grow, the expectation is that these technologies will enable unprecedented levels of operational capability and mission assurance. However, the use of additional communication technologies is not without cost. Network operators face considerable *tradeoffs* in the design and deployment of new systems, and the complexity inherent in large-scale wireless communication systems means that even basic analyses often resist intuition. Simple questions such as "Will more radios make the system better?" can be difficult to answer.

This study examines a particular tradeoff inherent in the fielding of wireless communication systems. Specifically, we study the effect of radio density on various aspects of wireless network performance. As a case study, we focus on a particular wireless communication system: the Enhanced Position Location Reporting System (EPLRS). We consider two possible bases of issue for the fielding of this system and examine how varying the number of fielded radios affects the system's ability to support Army communications requirements. We evaluate network performance by decomposing the problem into two subproblems, which we denote as the "network formation problem" and the "performance assessment problem." In the network formation problem, we seek to understand how the physical placement of individual radios leads to a routable network on which communication traffic can flow. Then, given a capacitated network topology on which traffic can be routed, we measure the performance of the network in terms of its ability to handle a specific demand for end-to-end traffic using predetermined protocols, or rules, for prioritizing and routing traffic.

To address the performance assessment problem, we model network operations in three ways. The first model provides an idealized representation of network performance by calculating total throughput in the best case. The second model estimates the percentage of potential end-to-end circuits that can be established simultaneously using a greedy heuristic and in a manner consistent with EPLRS design. The final model examines the ability of the network to support the distribution of situational awareness information using a discrete event simulation that computes the percentage of successful transmissions for networks of varying radio densities.

We exercise these models under various deployment scenarios and make recommendations regarding the fielding of these systems. Our findings indicate that while a modest increase in network density need not have a significant detrimental impact on network performance, it can pose additional challenges from a network management perspective. A larger network is not only more difficult to manage properly, but can also be much more sensitive to *improper* management. We conclude by making recommendations for further research that may facilitate future network design and performance evaluation efforts.

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This report extends the research in

> Fry, W. J. (2010). “An analysis of mobile ad-hoc network performance to recommend a basis of issue for the U.S. Army Nett Warrior System.” M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA.

Excerpts of that thesis also appear in this report.

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I. INTRODUCTION AND BACKGROUND

Advances in information technology are yielding dramatic changes in the use of real-time information sharing to support military operations in complex environments. The modern battlefield is increasingly dependent on high-speed, high-capacity communications networks to help maintain situational awareness and ultimately to support military command and control. Wireless networks are essential for communication in austere environments such as battlefield operations and post-disaster humanitarian assistance efforts. As the military use of wireless devices and services continues to grow, the expectation is that these technologies will enable unprecedented levels of operational capability and mission assurance.

However, the use of additional communication technologies is not without cost, and network operators face considerable *tradeoffs* in the design and deployment of new systems. Specifically, as the operational space becomes inundated with new wireless devices and services, the overhead of these systems becomes a greater concern. For example, because individual soldiers are limited in the amount of equipment that they can wear or carry, communication devices must be small and lightweight, while making efficient use of energy to extend limited battery life. In addition, the individual soldier typically has limited attention available to operate these technologies, and too many of them can be distracting. Finally, there are limits in the capacity of the wireless radio spectrum itself, and the overall performance of a wireless communication network depends on the quantity and placement of radios, each of which have the potential to interfere with the others. Understanding the potential costs of technology deployment can be as important as assessing the potential benefits of their use.

To address these challenges, researchers and technologists have devoted considerable effort to physical models of radio transmission and to the development of new technologies that allow for ad-hoc network construction. As a result of their success, we are now better at mass producing and deploying wireless communication devices than we are at understanding how they will perform in the field. Even simple questions such as "Will more radios make the system better?" are not easy to answer.

The objective of this research is to assess some fundamental tradeoffs in the deployment of and operation of wireless technologies, as is common with Mobile Ad-Hoc Network (MANET) systems. We explore several basic models of network performance and consider the impact that fielding additional radios has on them. Following the work of Fry (2010), we consider a specific MANET system consisting of Raytheon Corporation's Enhanced Position Location Reporting System (EPLRS) radios, which are currently in use by the U.S. Army, Navy, Marine Corps, and Air Force. Our results indicate that while small increases from the baseline deployment scenario do not necessarily result in significantly degraded network performance, they do pose an additional challenge for network management. We provide some guidance for identifying possible scenarios in which network management may become problematic, and we identify directions for future research.

A. PROBLEM OVERVIEW

MANET communication systems can support diverse military missions in a wide variety of scenarios. This flexibility makes them an important tool for military operations, but it also raises difficulties in the identification of canonical "use cases" against which to evaluate network performance. However, there are common features to all MANET problems that we review as a starting point for our analysis.

Figure 1 illustrates the overall network evaluation task in terms of two subproblems, which we denote as the "network formation problem" and the "performance assessment problem."

The Network Formation Problem. As a first step, we seek to understand how the physical placement of individual radios leads to a network on which communication traffic can flow. Given the locations of any two radios, their transmission power settings (and any technology-specific configuration), the ground terrain, and

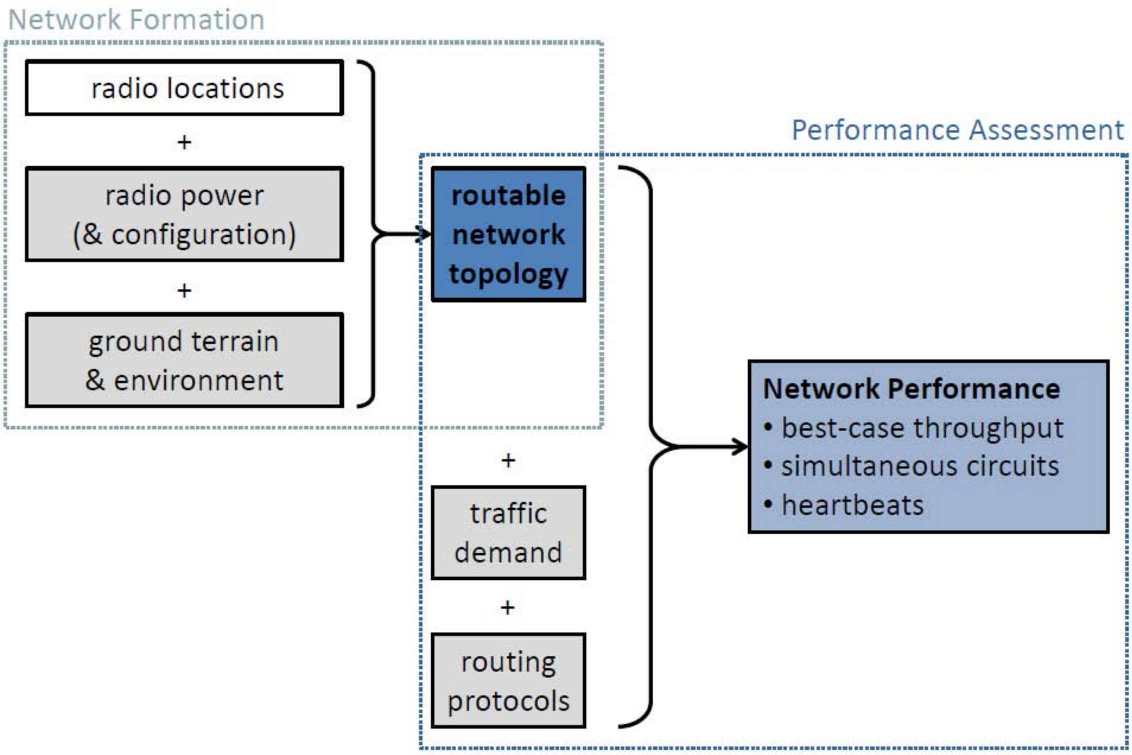


Figure 1. MANET network formation and performance assessment.

environmental conditions, we can compute the total capacity (in bits) of a directed transmission between them. Because radios often have minimum threshold requirements for the strength of received signals, not all radios will be able to communicate with one another. For a collection of radios that are dispersed over some operating region, this results in a network of individual transmission links.

The output of the formation problem is what we call a “routable network topology,” meaning that it represents the collection of potential paths that can be used for routing communication traffic.

The Performance Assessment Problem. Given a capacitated network topology on which traffic can be routed, we measure the performance of the network in terms of its ability to handle a specific demand for end-to-end traffic using predetermined protocols, or rules, for prioritizing and routing traffic.

There are several ways to measure the performance of a MANET system. We consider three ways—maximum total throughput, maximum number of simultaneous end-to-end circuits, and the ability to broadcast regular position update (or "heartbeat") messages.

B. EPLRS AS A CONCRETE EXAMPLE

While the network formation and performance assessment problems, as described above, are general, we focus on a specific type of technology in our analysis, namely the Enhanced Position Location Reporting System (EPLRS).

1. EPLRS Background

The U.S. Army began development of EPLRS as a follow-on program to the United States Marine Corps (USMC) Position Location Reporting System (PLRS) during the later stages of the Vietnam War. PLRS was originally intended to assist in the prevention of fratricide through better situational awareness of the battle space. Using PLRS as a starting point, the EPLRS program was originally designed in the late 1980s to deliver the geolocation functionality now provided by the Global Positioning System (GPS), allowing commanders to keep track of troop positions. EPLRS has since been adapted for use in MANET applications.

Since its initial development, the EPLRS program has gone through several iterations, each one increasing the system's capabilities and reducing its physical footprint. In its current implementation, EPLRS provides rapid, jam resistant, and secure data transfer to provide enhanced situational awareness and improved command and control (C2). EPLRS provides a "digital backbone" for the tactical networks utilized by a host of C2 applications, including Force Battle Command Brigade and Below (FBCB2) and the Army Battle Command System (ABCS).

The U.S. Army Nett Warrior System (NW), formerly the Ground Soldier System (GSS), is a type of MANET that uses EPLRS radios to enhance situational awareness and communications within a U.S. Army Brigade Combat Team (BCT). The Army relies on this system to provide valuable situational awareness and data transfer capabilities to its forces.

2. EPLRS Features

Fry (2010) provides a detailed description of EPLRS technical details and usage. However, we highlight several key features relevant to our analysis.

- *EPLRS provides robust, jam-resistant communication links that do not interfere with one another.* Each EPLRS Radio System (RS) uses frequency division multiplexing across several different *channels* and additionally separates transmissions among discrete *timeslots* in order to prevent traffic collisions within a single channel, minimize mutual interference, and increase network capacity. EPLRS also uses frequency-hopping techniques to minimize the effects of jamming.
- *Each EPLRS radio is capable of transmitting at different power levels*, often selectable by the user.
- As with all wireless systems, the capacity of an individual link depends on the location (and configuration) of the transmitter and receiver, the transmission power, the terrain, and the environmental conditions.
- The basic unit of end-to-end communication in an EPLRS network is a virtual circuit, known as a *needline*. Each needline is defined in terms of a type and waveform mode, timeslots, and frequency channels assigned to it. These configuration settings directly affect needline capacity, data rate, range, and error resiliency. Needlines are either *permanent*, in the sense that they are preplanned and remain throughout the deployment period, or they can be *dynamic*, that is, created when a need exists and then are terminated when communications are complete. Needlines can support either many-to-many (broadcast) or one-to-one (duplex) communication between radios.
- Each RS can participate in up to 32 needlines simultaneously; however, the maximum number is typically limited to 28 because of the timeslots used by the *coordination network*, a logical network that carries control traffic.
- To route a message across an EPLRS needline, a RS broadcasts the message to one or more neighboring RSs in the needline, who rebroadcast the message to their neighbors, and so on until the message reaches its destination. We refer to each relay as a "hop" along the overall route. In order to prevent an infinite echo of messages within the network, EPLRS uses a user-defined parameter called the *relay coverage*, which defines the maximum number of retransmissions allowed for each message. *Thus, there is a maximum number of hops a message may traverse on its way to its destination. For duplex*

needlines, this maximum is five hops. The downside to this approach is that the RS transmitting the original message must wait until each message has reached its hop limit before sending the next one. This ensures that different messages are not being retransmitted through the network simultaneously, but it also results in a significant reduction in the overall capacity of the network to carry traffic.

- An individual known as the EPLRS *Network Planner* is responsible for the planning and management of the deployed network, including the designation and initialization of needlines.

We evaluate EPLRS network performance by several methods. First, we evaluate *point-to-point connectivity* based on the physics of wireless communications and its impact on network topology. Second, we assess the capacity of the network, both in terms of total weighted throughput and also the total number of simultaneous needlines that it can support. Finally, we measure the ability of different network topologies to broadcast situational awareness information specific to EPLRS.

Intuitively, one expects that network connectivity will improve as the number of radios increases, but there is more to performance than simple connectivity. We explore several key tensions in the deployment of MANET systems. First, small changes in the quantity and geographic dispersion of wireless radios can have a big impact on the resulting network topology. In general, issuing more radios does lead to greater connectivity, as measured by the total number of available communication links. However, the deployment of additional radios also means greater competition for common network resources, which can actually reduce network performance as a whole. Understanding these tradeoffs is crucial for network designers and operators.

C. LITERATURE REVIEW OF PREVIOUS WORK

Xiao, Johansson, and Boyd (2004) present a formulation for MANET design that maximizes the flow of traffic across a wireless network by optimally allocating communication resources. This Simultaneous Routing and Resource Allocation (SRRA) problem easily decomposes into two major subproblems: network flow and communication resource allocation. We use a similar framework to calculate network performance within the constraints of our specific application.

Shankar (2008) uses the SRRA framework to determine optimal jammer placement in order to disrupt wireless network communications. He combines the SRRA definition of network flow with the attacker-defender techniques of Brown, Carlyle, and Wood (2006) to identify the maximum disruption of traffic flow.

Nicholas (2009) uses the SRRA formulation to identify the placement of wireless access points that maximizes a combination of signal coverage and network throughput. This application informs the design and deployment of wireless networks that rely on fixed access points to provide access to users in specific geographic regions. Nicholas achieves a high level of accuracy in the calculation of received signal strength using the standard link budget formula (see Olexa, 2005) with the free space loss term determined by the Terrain-Integrated Rough-Earth Model (TIREM) of Alion Science & Technology Corporation (2010). We use the same technique to calculate received signal strength.

Smith (2009) uses discrete event simulation to model the performance of three different wireless networking devices: EPLRS, the Single Channel Ground and Airborne Radio System (SINCGARS), and the Cooperative Diversity Radio. He examines average throughput and message completion rate as a measure of overall network performance. Smith uses a commercial simulation software suite known as the Joint Communications Simulation System (JCSS), maintained by the Defense Information Systems Agency (DISA). In his study, Smith fixes certain variables in an effort to aid comparison, but as a result, the simulated operation is not necessarily representative of how a properly planned and deployed system would function in a real-world scenario. The result is an underestimation of actual EPLRS network performance.

The U.S. Army Training and Doctrine Command (TRADOC) Analysis Center Monterey (TRAC-MRY) initiated a study to examine the performance of the NW system as a function of EPLRS radio density (see Evangelista, 2009). The TRAC-

MRY study uses the probability of *line of sight* (LOS) between nodes and the message range probability, defined as the likelihood of successful traffic delivery as a function of range. The objective is to understand how varying the number of radios fielded affects the system's ability to support Army communications requirements. Specifically, the study considers two bases of issue: the squad leader basis of issue (SL BOI) and the denser team leader basis of issue (TL BOI) (see Figure 2).

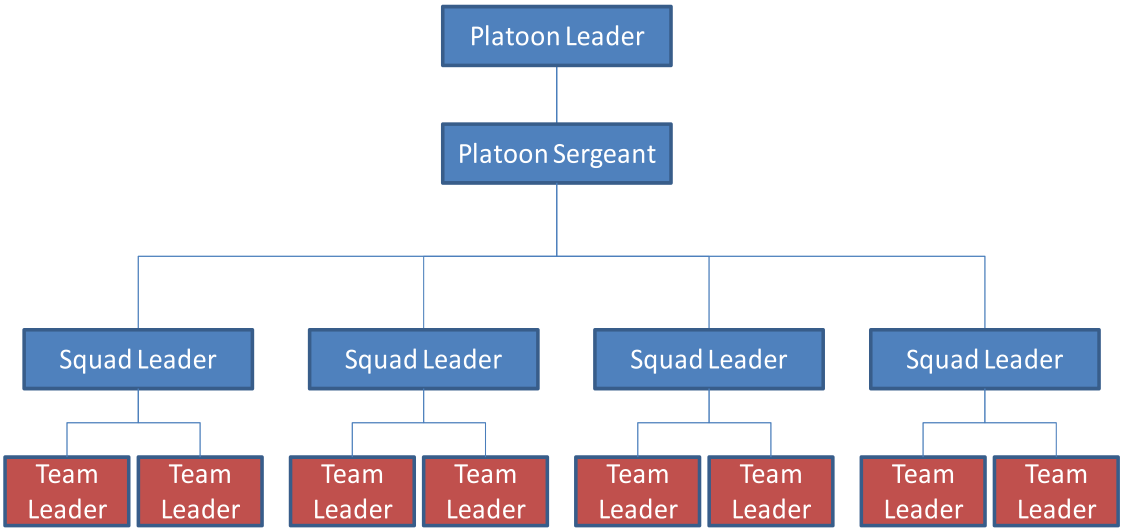


Figure 2. Organization of an Army platoon. For a brigade of three platoons, issuing radios down to squad leaders (SL BOI) results in a total of 18 radios, while issuing radios down to team leaders (TL BOI) results in a total of 42 radios.

The TRAC-MRY study indicates that the TL BOI is the recommended employment strategy since it yields a network with a greater number of links present between nodes. What the TRAC-MRY study does not consider, however, is how an increase in node density changes network performance.

Fry (2010) builds on the work of Evangelista by extending the analysis of network performance beyond simple connectivity. This report summarizes the major results of Fry (2010) in a broader context of and discusses directions for future research.

II. TOPOLOGY MODELING

In order for MANET systems and other wireless networks to be useful in a variety of scenarios or environments, the underlying architecture of these systems must support, in principle, arbitrary connectivity of their radios. It is well-understood that although the *correctness* of a communications network (i.e., the ability of a network to route traffic successfully) should not depend on its topology, the *performance* of the network (e.g., its total throughput) can depend greatly on it. For example, a sparsely connected network with low capacity links can support less traffic and is more fragile than a well-connected network with high link capacities. Thus, a first step in assessing the performance of a wireless network is to understand its topology.

For a wireless communications network, we represent an individual radio as a *node*, and we use a *link* to represent the potential for a directed transmission between a pair of nodes. By *topology*, we mean the set of all directed transmission links that are available in the network, along with each link's *capacity*, i.e., the maximum rate at which we can transmit data on it.

The physics of wireless communications are relatively straightforward from a theoretical standpoint, but there are a large number of factors that affect radio transmission, and in practice, many of these are in constant flux. The result is that radio transmission rarely behaves according to the theoretical ideals. Nonetheless, we can think of wireless network topology most simply as a function of (1) radio locations, (2) radio transmission power, and (3) the ground terrain and environment (see Figure 3).

In this chapter, we examine how the relative position of radios, transmit power, and other EPLRS-specific settings affect wireless network topology. We begin with a review of received signal strength and the way that it determines link capacity.

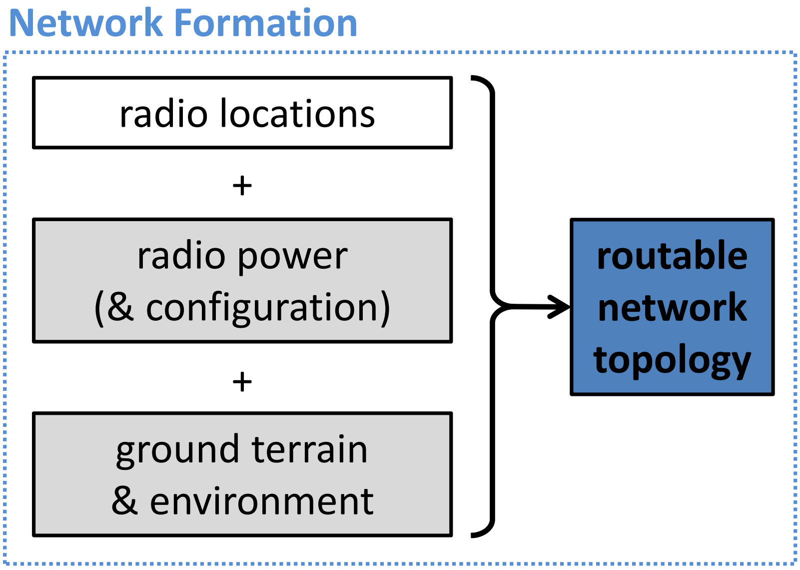


Figure 3. A simplified view of MANET network formation.

A. RECEIVED SIGNAL STRENGTH AND LINK CAPACITY

The link capacity between two nodes is primarily determined by the *received signal strength* (RSS) between the nodes. In general, received signal strength is a function of transmitter power, distance between transmitter and receiver, and the interference and/or losses along the transmission path.

We calculate received signal strength ρ for an arc $(i, j) \in A$ according to the standard link budget formula (see Olexa, 2005),

$$\rho_{ij} = P_{tx} - g_{tx} - L_{tx} - L_{fs} - L_m - g_{rx} - L_{rx}, \qquad \text{(II.1)}$$

where P_{tx} is transmitted power in dBm, g_{tx} and g_{rx} are, respectively, the antenna gains of the transmitter and receiver in dBi, L_{tx} and L_{rx} are, respectively, the losses (i.e., from cables, connectors) of the transmitter and receiver in dB, L_{fs} is free-space path loss in dB, and L_m is miscellaneous loss (i.e., fade margin) in dB. We assume nominal values for the antenna gains, transmitter and receiver losses, and miscellaneous losses, as shown in Table 1.

Transmitter Antenna Gain (g_{tx})	3 dBi
Receiver Antenna Gain (g_{rx})	3 dBi
Fade Margin (L_m)	30 dB
Transmitter Losses (L_{tx})	0 dBm
Receiver Losses (L_{rx})	0 dBm

Table 1. Received signal strength calculation assumptions.

Free-space path loss, L_{fs}, is the decrease in signal strength that results from the transmission of an electromagnetic wave along a line-of-sight path through free space. It can be determined using one of several methods. One simple method for determining free-space path loss uses the inverse-square path loss model, as implemented by Xiao et al. (2004). Using this approach, the decrease in received signal strength is proportional to the inverse square of the distance between receiver and transmitter. The inverse-square path loss model represents the inverse of free-space path loss in Watts as

$$\frac{1}{L_{fs}} = \left(\frac{y_0}{y_{ij}}\right)^2 p_i, \tag{II.2}$$

where y_0 is some reference distance, y_{ij} is the distance between two radios i and j, and p_i is the transmission power at radio i in Watts. This method provides a simple, yet crude, representation of path loss.

Another method commonly employed for the determination of path loss is the Terrain-Integrated Rough-Earth Model (TIREM) of Alion Science & Technology Corporation (2010). In addition to free-space losses, TIREM also accounts for losses due to atmospheric and ground effects. It also uses the Spherical Earth Model (SEM) to account for the curvature of the Earth in determining whether LOS exists between transmitter and receiver. Inputs to TIREM include the terrain profile between transmitter and receiver, information about the transmitter (antenna height, frequency, antenna polarization), the receiver (antenna height), atmospheric constants (surface refractivity, humidity), and ground constants (relative permittivity, conductivity). It provides very accurate estimates of path loss, but its major limitation is that it does not consider attenuation due to rain, foliage, or man-made obstacles. TIREM serves as the underlying path-loss model in many commercial simulation software platforms, including Analytical Graphics' Satellite Toolkit (STK) Suite and the Defense Information Systems Agency (DISA) Joint Communications Simulation System (JCSS).

In this work, we use TIREM to determine the path loss between transmitter and receiver. We assume nominal values for the TIREM inputs, shown in Table 2 and adapted from Nicholas (2009). We also assume a flat terrain profile, which results in an upper bound on actual received signal strengths.

Input Parameter	**Value**
Transmitter Frequency	450 MHz
Transmitter Antenna Height	2 m
Receiver Antenna Height	2 m
Antenna Polarization	Horizontal
Surface Refractivity	300 N-units
Humidity	5 g/m^3
Relative Permittivity of Earth's surface	25
Conductivity of Earth's surface	50 S/m

Table 2. TIREM inputs (From Nicholas, 2009).

Although TIREM provides the most realistic representation of path loss, any of the models described above and in Fry (2010) are valid methods to compare relative RSS values. It is noteworthy that the qualitative results obtained using any of the path loss models are similar, and the only significant differences we see are in the absolute scale of the calculated received signal strengths.

Once we calculate the received signal strength between two nodes, we can use it to determine the capacity (i.e., data rate) than can be achieved between those nodes. A theoretical upper bound on link capacity, measured in bits per second (bps), comes from the classical Shannon Capacity Formula (see Shannon, 1949), which states

$$\begin{aligned} \text{Link Capacity} &\equiv b\log_2\left(1+\frac{Signal}{Noise}\right) && \text{(II.3)} \\ &= b\log_2\left(1+\frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{n_j\left(10^{\frac{L_{fs}+L_m}{10}}\right)}p\right) && \text{(II.4)} \end{aligned}$$

where n_j represents the background noise at receiver j. This capacity represents the expected throughput, in bps, between a transmitter and receiver.

EPLRS radios can operate at four different power settings: 0.4 W, 3 W, 20 W, and 100 W. We evaluate the Shannon capacity for each of the four selectable power levels in EPLRS to obtain an upper bound on link capacities as a function of distance, as seen in Figure 4. This limit represents system performance under ideal conditions and does not account for limitations within EPLRS, which in reality result in lower observed throughput values.

In wireless communications, received signal strength dictates whether two nodes are able to establish and maintain a connection, which we define as the ability for one node to pass traffic to the other at a particular minimum data rate. In order for a connection to exist, the received signal strength must exceed some minimum threshold. Following Fry (2010), we assume this threshold to be –98 dBm for this study (this is based on the average of the published *90% Burst Throughput* levels for EPLRS waveforms). When it drops below the threshold, the connection is “lost” and the nodes are no longer able to exchange traffic directly. A decrease in received signal strength can be the result of varying any of the inputs to Equation II.1. Increasing

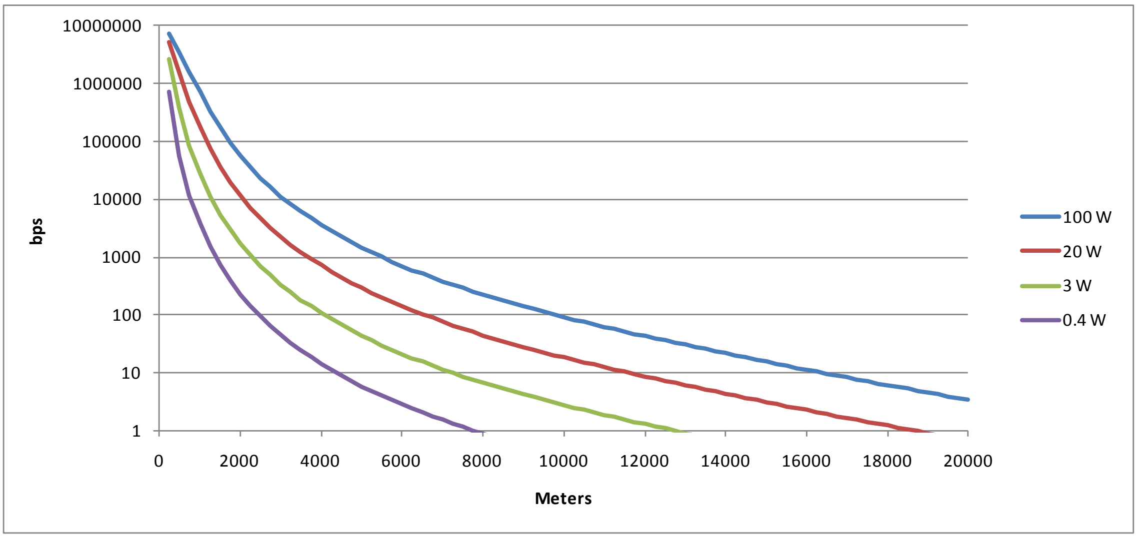


Figure 4. Calculated Shannon link capacities for EPLRS power settings.

the distance between nodes, reducing transmitter power, or increasing background noise at the receiver all serve to reduce the received signal strength and eliminate connections between nodes.

B. RADIO DISPERSION AND NETWORK TOPOLOGY

The topology, as defined by the presence and capacity of individual wireless links, of a mobile ad-hoc network depends on the location of radios, their transmission power, and the ground terrain, among other things. When the geographic distances between nodes are short, transmitter powers are high, line of sight is clear, and background noise is minimal, then the received signal strengths are all relatively high, and each node is capable of broadcasting its traffic directly to the intended recipient without the need for message relay by intermediate nodes (see Figure 5 Left).

If conditions change, and received signal strength decreases, we see a shift in topology from a direct, point-to-point, broadcast regime to something that acts as a true network, requiring routing through relay nodes to facilitate traffic delivery (as illustrated in Figure 5 Right). In this section, we study the impact of radio placement on the topology and performance of the resulting routable network.

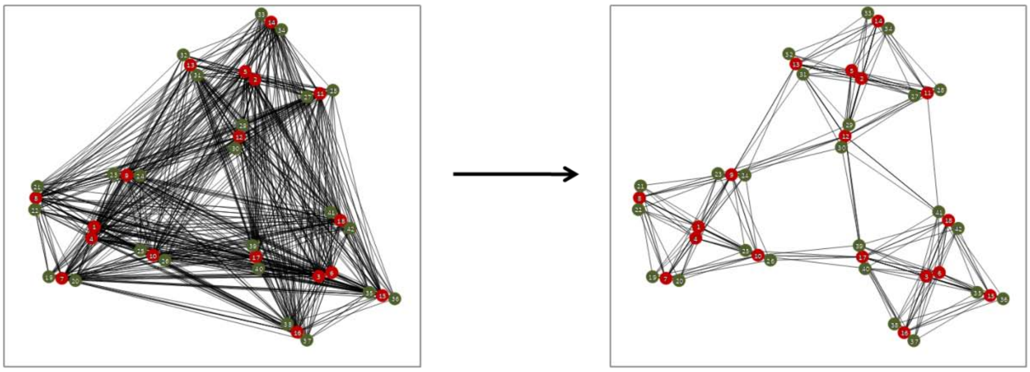


Figure 5. Effect of reducing received signal strength. Left: If RSS is high, then each node can transmit directly to another, and the topology looks like a fully connected graph. Right: If the RSS is sufficiently lower, then only nearby nodes can transmit directly with one another and the topology looks more like a sparse mesh.

We introduce a model of the spatial *dispersion* of radios within the battle space. This dispersion model prescribes the relative locations of units, specifically the distances between them, which contribute to the connectivity between the nodes on the network. Other factors affecting connectivity are line-of-sight and terrestrial and atmospheric effects.

We base the dispersion model in this work on a nominal geometric dispersion pattern consistent with previous EPLRS network density research (see Evangelista, 2009). We start by identifying the geographic center of the company. We then position three platoons some distance from this center point, referred to as the *platoon dispersion* parameter, with each platoon at 120° radial spacing. From each platoon point, we distribute four squads in a similar manner using 90° radial spacing and at a distance defined by the *squad dispersion parameter*. Finally, we distribute two teams from the squad points using 180° radial spacing and a distance defined by the *team dispersion parameter*. We offset an additional node from the platoon point to represent a second command element at the platoon level. This dispersion pattern results in the placement of 42 nodes in the TL BOI, as compared to 18 nodes in the SL BOI, illustrated in Figure 6.

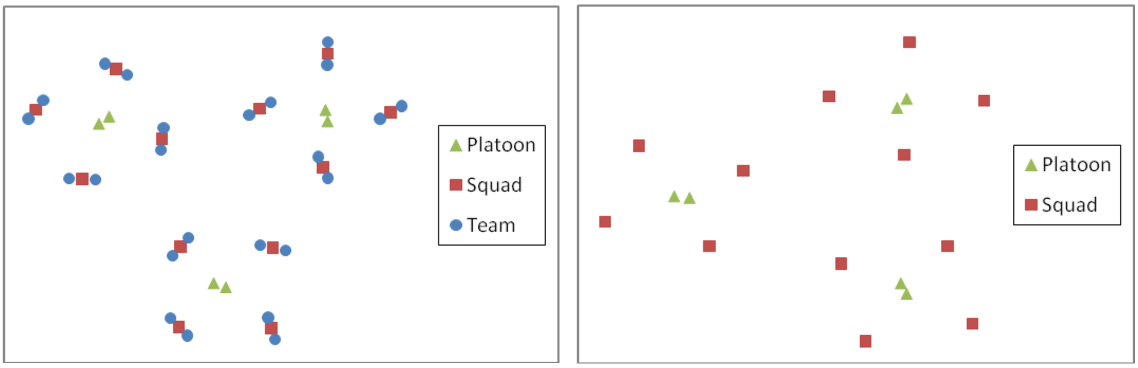


Figure 6. Example of Team Leader BOI node dispersion (left) and Squad Leader BOI node dispersion (right).

To examinate the effects of varying distances between nodes, we introduce a *Dispersion Factor* that is multiplied by the values in Table 3 to provide values for the platoon, squad, and team dispersion parameters described above.

Dispersion Parameter	**Multiplier**
Platoon	100 m
Squad	50 m
Team	20 m

Table 3. Dispersion model parameters.

Qualitatively, greater geographical dispersion results in a more sparsely-connected network topology. Eventually, the decreasing signal strength causes platoons to lose connectivity altogether, as seen in Figure 7. However, the true impact of geographical dispersion on the network performance can only be seen by examining the network's ability to route traffic, as described in the next section.

This model of dispersion assumes *uniform* spacing, in the sense that the parameters in Table 3 ensure that the relative positions of radios "grow" or "shrink" together. By changing the values of these parameters, one changes the relative proportional spacing between radios. While this type of dispersion may be reasonable

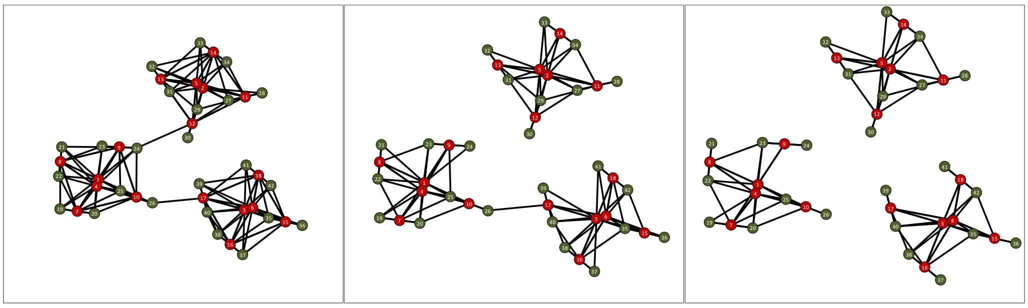


Figure 7. Loss of platoon connectivity.

in relatively “open” spaces, it might not be realistic in environments where soldiers organize themselves differently (e.g., in convoys along a road segment).

1. ANALYSIS: Homogeneous Deployment

We first consider a scenario involving homogeneous distribution of 5 W radios only, illustrated in Figure 8.

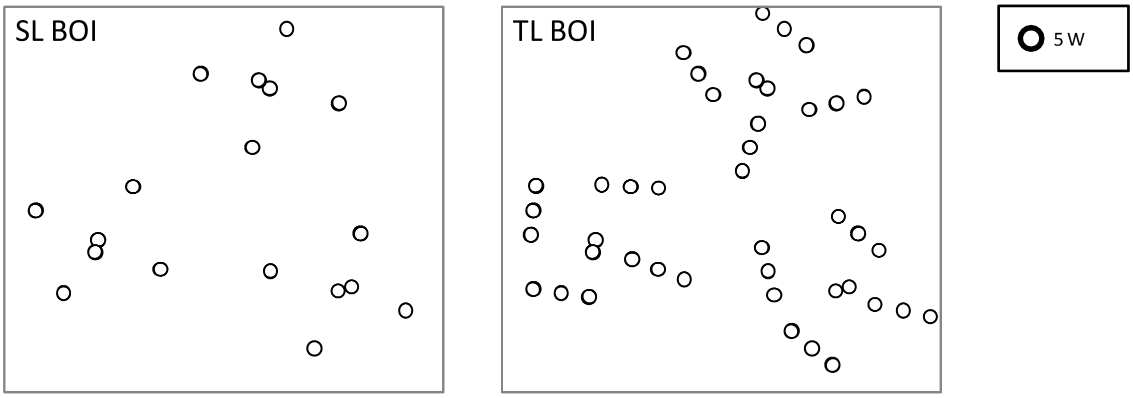


Figure 8. Radio dispersion—homogeneous (5 W).

We start with a dispersion factor of one, meaning that nodes are spaced according to Table 3. In this case, radios are so close that the network is completely connected and every node is capable of connecting to any other node directly. We then increase the dispersion factor, which “stretches” the nodes apart. As this happens, the received signal strength of each link decreases. When the received signal strength of a link reaches the –98 dBm threshold, connectivity between nodes is lost.

Figure 9 illustrates the decrease in total number of network links as the network is more greatly dispersed. Because the SL BOI has a total of 18 nodes, there are a maximum of 306 possible links, which are realized when all radios are close together. In contrast, the TL BOI has 42 nodes and therefore a total of 1,722 possible links, which are realized when all radios are close together. Although the TL BOI has many more possible links, the decrease in the actual links for greater dispersion values is qualitatively similar to the SL BOI.

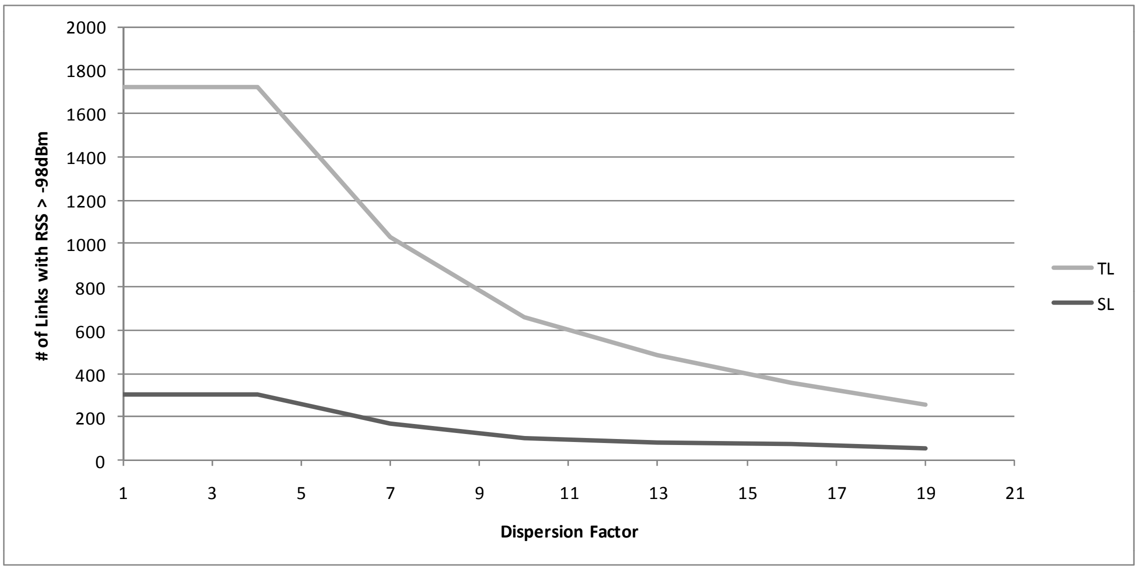


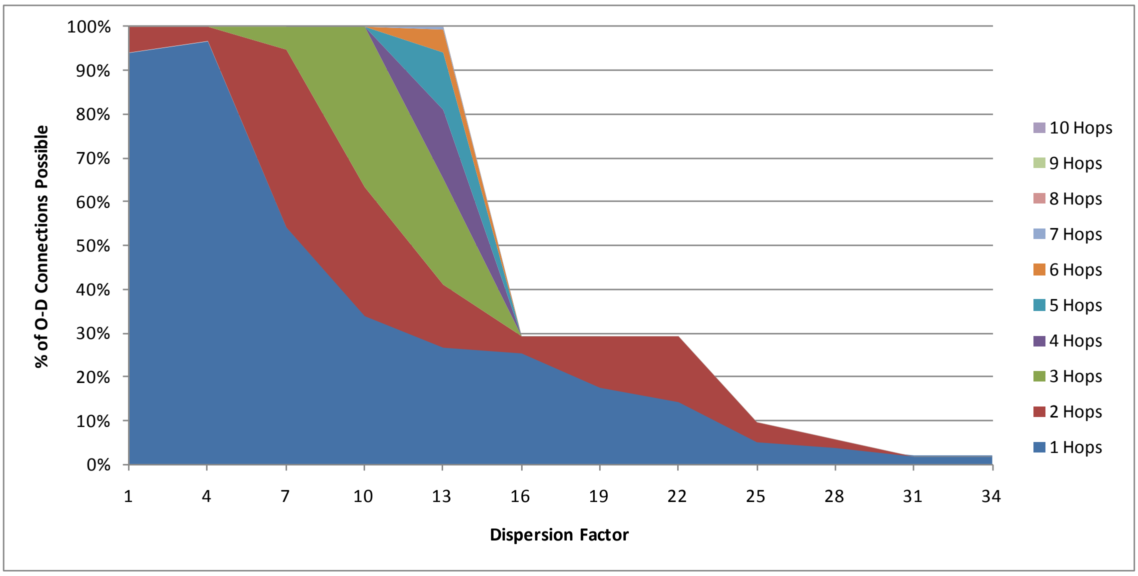
Figure 9. Total number of network links as a function of radio dispersion. Homogeneous case: all radios are 5 W.

Even when individual links are lost, teams, squads, and platoons can remain connected through intermediate radios that act as message relays. Next, we examine the ability of this homogeneous network of 5 W radios to support end-to-end connections by routing traffic through intermediate nodes. Each time traffic is forwarded via an intermediate node, we refer to this as a *hop*. Paths with few hops are preferable to paths with many hops, as they result in lower latency, less interference, and less overall energy consumption. Also, as noted before, EPLRS duplex needlines can have at most five hops. We examine how many hops it takes to connect every pair of nodes. Figure 10 shows the percentage of origin-destination (O-D) pairs that can connect within a given number of hops, across a range of dispersion factors for the SL BOI.

We see that 100% of O-D connections are possible until the platoons become disconnected, and that no origin-destination pair uses more than seven hops. Figure 10 (Bottom) shows that in the TL BOI, the network is able to support 100% of the connections to higher dispersion factors due to the presence of more radios acting as relays. We see that as the dispersion factor increases, more hops are required to maintain 100% connectivity.

Comparison of the two bases of issue in a homogeneous deployment scenario highlights the increased connectivity that results from a greater number of radios.

It is important to note that slight changes in the angular orientation of the platoons can affect the ability of a squad leader or team leader to act as a relay between platoons, and thus change the exact point at which disconnection happens. However, we believe that the results here are qualitatively consistent for different orientations of platoons.



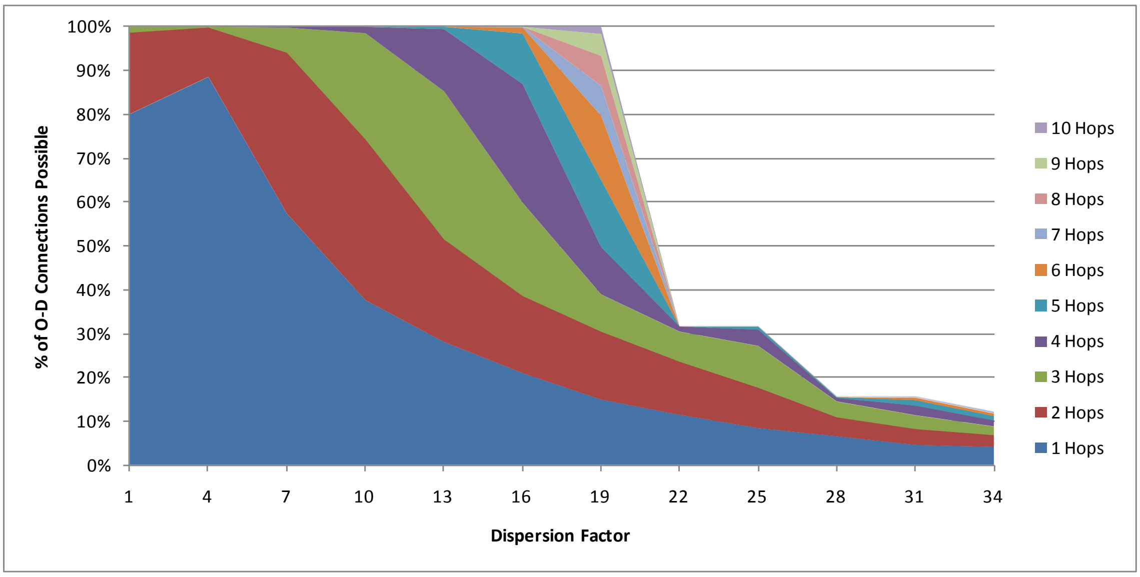


Figure 10. Number of hops required to connect each origin-destination (O-D) pair of radios. Top: homogeneous, 5W, SL BOI; The network becomes disconnected at a dispersion factor of about 13, after which less than 30% of O-D pairs are connected. Most end-to-end connections require 1-3 hops. Bottom: Homogeneous, 5W, TL BOI; the network stays connected at wider dispersion because it uses the additional radios as relays, also increasing the number of end-to-end connections requiring 4-10 hops. Since EPLRS duplex needlines are constrained to a maximum of five hops, the mere existence of an end-to-end connection is not necessarily enough to ensure the ability to communicate.

2. ANALYSIS: Heterogeneous Deployment

We consider a second scenario, in which we explore the effects of a heterogeneous deployment of RSs. We assume that the Platoon Leaders, Platoon Sergeants, and Squad Leaders have 100 W radios and the Team Leaders have 5 W radios. The resulting network dispersions are shown in Figure 11.

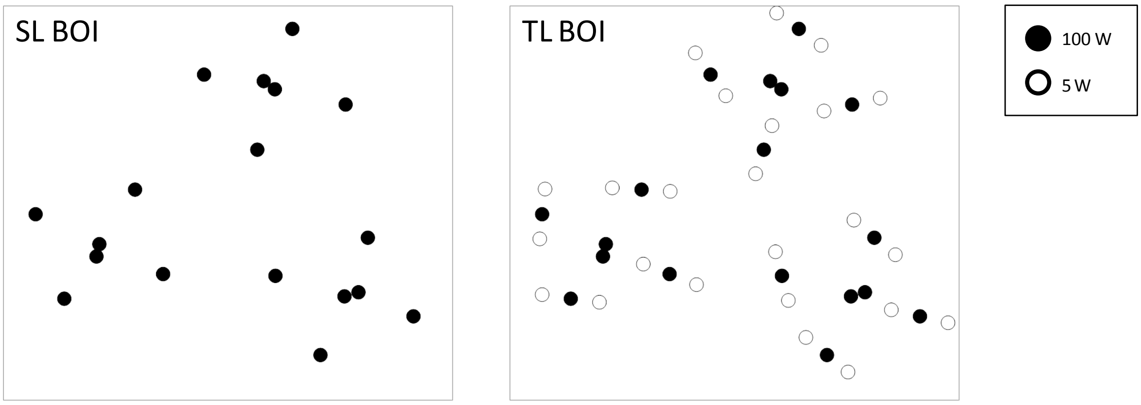


Figure 11. Radio dispersion—heterogeneous (100W, 5W).

An obvious benefit of the high power setting is that connectivity is maintained at much greater distances, represented here by higher dispersion factor values. The decline in connectivity for the heterogeneous case, as measured in Figure 12, is qualitatively similar to the homogeneous case, but extends to a maximum dispersion value almost twice that in Figure 9. However, operation of the system at high transmit powers increases the risk of jamming, electronic countermeasures, and signal interception.

Figure 13 illustrates the ability of this heterogenous network radios to support end-to-end paths by routing traffic through intermediate nodes.

Intuitively, deployment of the 100 W radios increases the distance, as measured in dispersion factor, to which 100% connectivity can be maintained. Since the SL BOI does not issue radios to the Team Leaders, Figure 13 (Top) represents the equivalent homogeneous network with 100 W radios.

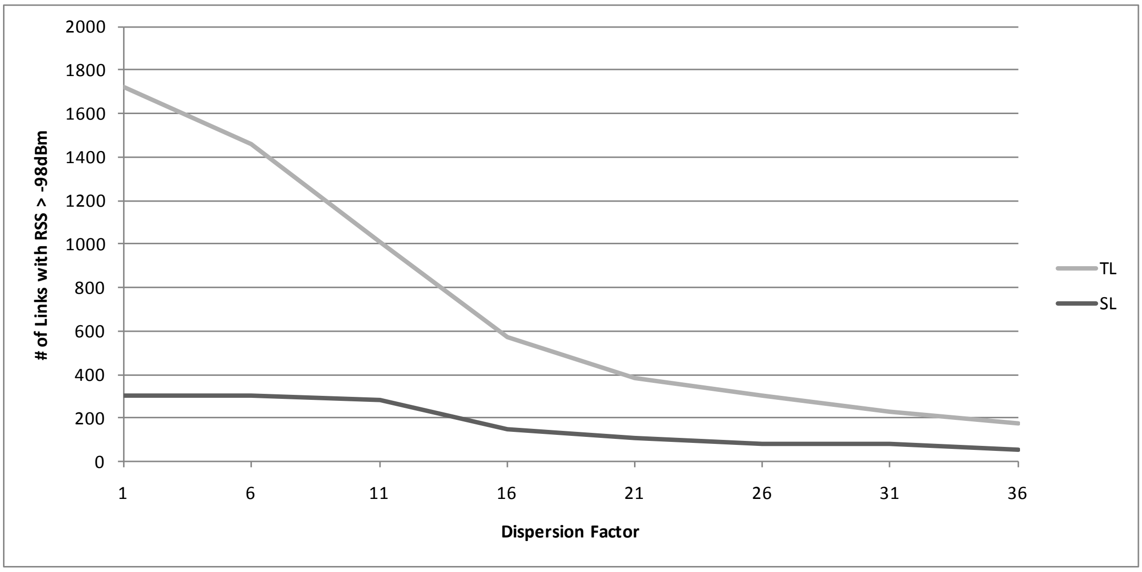
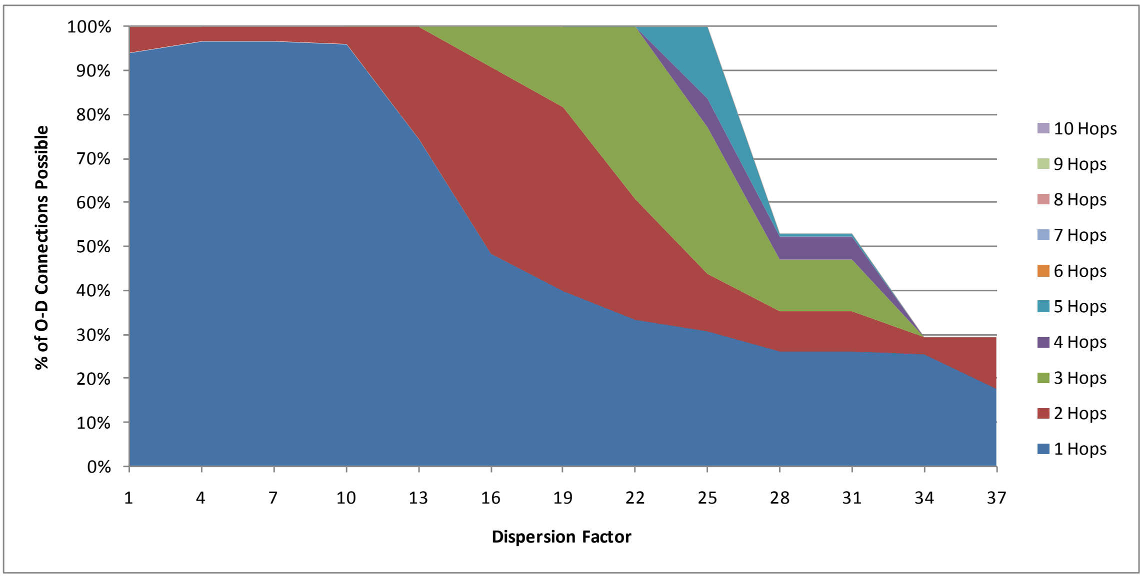


Figure 12. Total number of network links as a function of radio dispersion. Heterogeneous case: (100W, 5W).

A comparison within Figure 13 reveals that the introduction of additional 5 W radios enhances the network's overall connectivity at greater dispersion factors, as seen by the greater number of links of four hops and greater. The benefits of additional radios acting as relays, seen in the homogeneous deployment scenario, are also observed in the heterogeneous case.



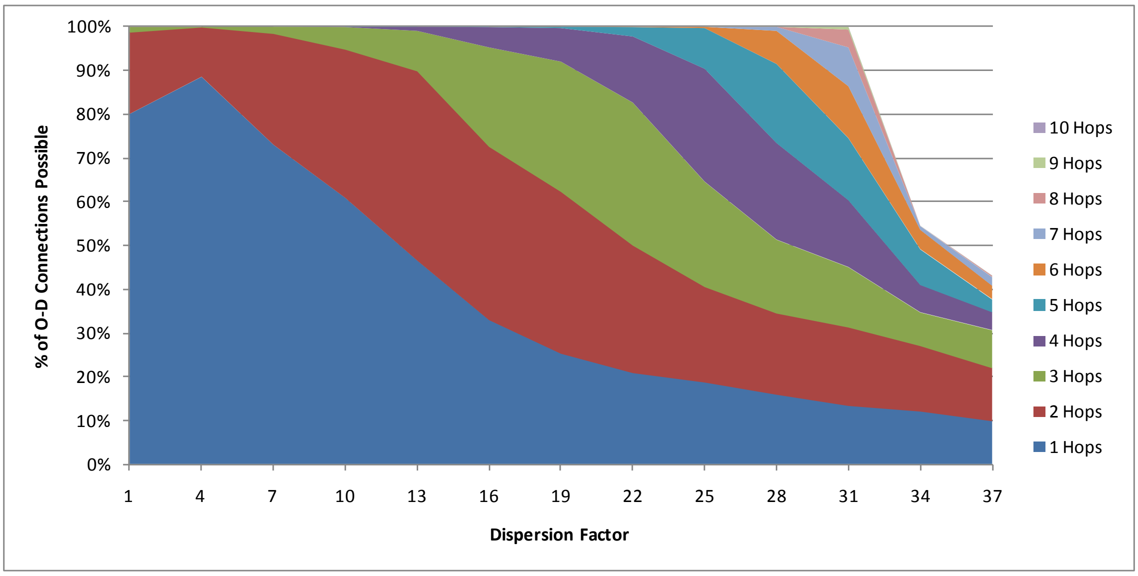


Figure 13. Number of hops required to connect each origin-destination (O-D) pair of radios. Top: heterogeneous, 100W-5W, SL BOI. Bottom: heterogeneous, 100W-5W, TL BOI. The use of high-powered radios allows for connectivity at significantly higher dispersion values.

C. CHAPTER SUMMARY

A first step in assessing the performance of a MANET is to understand how the location, transmission power, and configuration of radios, along with ground terrain and environmental factors, affects the network topology that is available for routing traffic. We can approximate the capacity of individual transmission links using models of free space transmission loss, such as TIREM, and information-theoretic capacity formulas. Using a model of uniform geometric dispersion, we assess the ability of the network to maintain connectiivty as radios are spread over larger distances.

III. NETWORK PERFORMANCE ASSESSMENT

Wireless networks are used to support many different types of communication and operational activities. As a result, there are many possible ways to assess the performance of a wireless network. As argued in the previous section, the performance of a MANET system can depend on the network topology, but it also fundamentally depends on the *demand* for network traffic as well as the *protocols* (or rules) for determining when and how that traffic is routed over the network (see Figure 14).

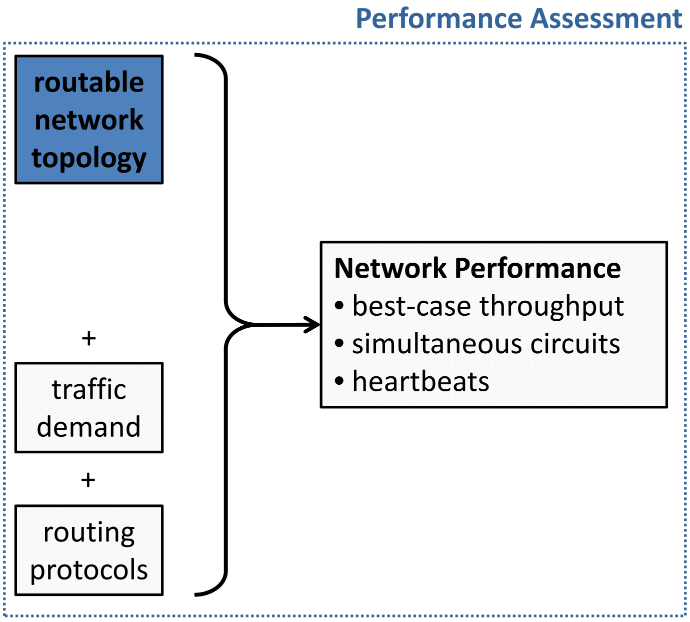


Figure 14. MANET performance analysis.

In this section, we consider three distinct measures of network performance that are pertinent to EPLRS-based MANET systems. The first measures total network throughput; the second measures network capacity for simultaneous end-to-end connections, and the third measures successful broadcast of position update (so-called "heartbeat") messages.

A. GENERALIZED THROUGHPUT: IDEALIZED SRRA

We start with a theoretical measure of network flow under ideal conditions, modifying the SRRA formulation presented by Xiao et al. (2004). The objective of SRRA is to maximize the utility of traffic flow across all nodes in the network, and the resulting flows provide an upper bound on network performance.

In what follows, we define N to be a set of nodes, indexed by i (alias j, k, d). We represent directed arcs $(i, j) \in A$, where A is the set of all arcs satisfying the received signal strength threshold. Applied to the context of EPLRS communications networks, each node represents an EPLRS RS, and each arc represents the wireless link between two nodes.

We represent data traffic across the network using a multicommodity network flow model, where commodities are defined by O-D pairs, a practice consistent with network routing and optimization literature (Ahuja, Magnanti, and Orlin 1993).We define X_{ij}^{d} as the flow along arc (i, j) destined for node $d \in N$, and we define S_{i}^{d} as the total flow originating at node $i \in N$ and delivered to node $d \in N$. The commodities flowing through the network are the bits of data transmitted from one node to another. In a typical multicommodity network flow problem, link capacities are fixed; however, in the context of wireless networking, link capacities depend on available communications resources as described by Equation II.4.

We build our model as an idealization of the EPLRS network. We ignore constraints specific to the operation of needlines; specifically, the maximum number of needlines per node and the maximum hop distances for needlines. Thus, our formulation is a relaxation of the real problem, and any solution represents an upper bound on total network throughput.

The complete mathematical formulation is shown in Figure 15.

Index Use

$i \in N$	node (*alias j,k,d)*
$(i, j) \in A$	directed arc

Calculated Data

ρ_{ij}	received signal strength per arc $(i, j) \in A$
b_i	maximum channel bandwidth per node $i \in N$
n_j	background noise per node $j \in N$
w_i^d	importance of traffic flow from node $i \in N$ destined for node $d \in N$

Decision Variables

S_i^d	total flow of traffic from node $i \in N$ destined for node $d \in N$
X_{ij}^d	traffic flow along arc $(i, j) \in A$ destined for node $d \in N$
T_{ij}	total flow along arc $(i, j) \in A$
F_{ij}	time-slot fraction of arc $(i, j) \in A$

Formulation

$$\max_{S,X,T,F} \sum_{d} \sum_{i:i \neq d} \log_2 \left(w_i^d + S_i^d \right) \qquad \text{(S0)}$$

$$\textit{s.t.} \quad \sum_{k:(j,k) \in A} X_{jk}^d - \sum_{i:(i,j) \in A} X_{ij}^d = S_j^d \qquad \forall j \in N, \forall d \in D \qquad \text{(S1)}$$

$$T_{ij} = \sum_{d} X_{ij}^d \qquad \forall (i, j) \in A \qquad \text{(S2)}$$

$$T_{ij} - F_{ij} b_i \log_2 \left(1 + \frac{\rho_{ij}}{n_j} \right) \leq 0 \qquad \forall (i, j) \in A \qquad \text{(S3)}$$

$$\sum_{j:(i,j) \in A} F_{ij} \leq 1 \qquad \forall i \in N \qquad \text{(S4)}$$

$$S_i^d \geq 0 \qquad i, d \in N,\ i \neq d \qquad \text{(S5)}$$

$$X_{ij}^d \geq 0 \qquad \forall (i, j) \in A,\ \forall d \in D \qquad \text{(S6)}$$

$$T_{ij} \geq 0 \qquad \forall (i, j) \in A \qquad \text{(S7)}$$

$$F_{ij} \geq 0 \qquad \forall (i, j) \in A \qquad \text{(S8)}$$

Figure 15. Idealized SRRA model formulation.

The objective (S0) maximizes the total utility of all network traffic flow from source node i to sink node d. In order to account for the different levels of importance of traffic passing through the network, the terms $w_i^d \in \{0, 1\}$ allow us to change the "weight" of each flow. When $w_i^d = 0$, we recover the original utility in Xiao et al. (2004), also used in Nicholas (2009). However, setting $w_i^d = 1$ effectively shifts the log utility function "to the left" resulting in a smaller penalty for flows that are near zero, shown in Figure 16. In practice, we set $w_i^d = 0$ for high priority traffic and $w_i^d = 1$ for low priority traffic. Thus, failure of the network to provide some flow for high priority traffic results in an infinite penalty, while zero flow for low priority traffic brings neither penalty nor benefit.

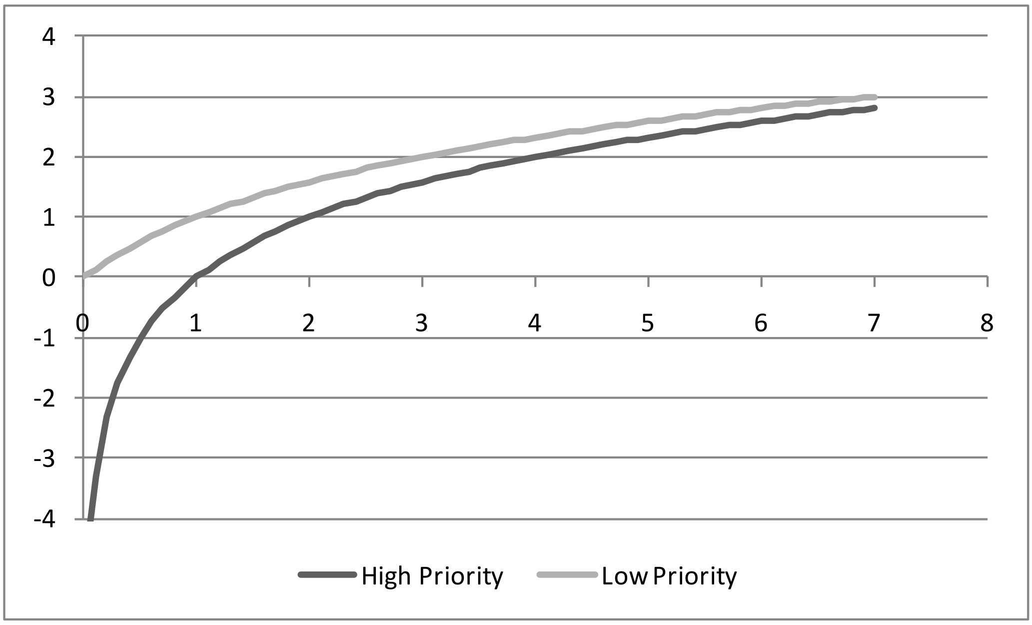


Figure 16. Effect of weighting on log utility function.

Constraints (S1) ensure "balance of flow" at each node, and constraints (S2) account for the total flow on each arc. The link capacity constraints (S3) take into account the time-division channel access method used by EPLRS RSs. Parameters of this constraint include the total available power and bandwidth for each source node as well as a time-slot fraction for each link (a version of this can also be found in Xiao et al. 2004). The assignment of a time-slot fraction to the link capacity constraint ensures the resulting capacity is consistent with a time-division channel access scheme. Using Equation II.4, the resulting constraint formulation is then

$$T_{ij} - F_{ij} b_i \log_2 \left(1 + \frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{n_j \left(10^{\frac{L_{fs}+L_m}{10}} \right)} p_i \right) \leq 0 \qquad \forall (i,j) \in A, \tag{III.1}$$

where T_{ij} is the total flow along arc $(i,j) \in A$, and F_{ij} is a decision variable that selects optimal time-slot fractions for each link. This is in contrast to actual EPLRS logical time-slot selection, which the network manager determines prior to deployment. Allowing the program to select optimal values for time-slot fraction yields an upper bound on the actual performance of the network. We simplify Equation III.1 by defining the received signal strength on arc (i,j) as

$$\rho_{ij} = \frac{10^{\frac{g_{tx}+g_{rx}}{10}}}{\left(10^{\frac{L_{fs}+L_m}{10}} \right)} p_i \tag{III.2}$$

and substituting to yield (S3). Constraint (S4) further constrains the acceptable values for the time-slot fractions so they sum to one. Constraints (S5-S8) enforce nonnegativity of the decision variables.

The optimal objective value of our SRRA problem is total network utility. We can recover the *total network throughput* as:

$$\text{Total Throughput} = \sum_i \sum_d S_i^d \qquad \forall i \in N, d \in D. \tag{III.3}$$

This provides an upper bound on network performance based on the physics of wireless communication under ideal operating conditions (i.e., perfect LOS, uniform background noise).

We examine network performance by solving our SRRA formulation and evaluating the total throughput (Equation III.3) across a range of dispersion factors. We perform this experiment on two possible transmit power scenarios.

First, we revisit the homogeneous scenario involving only 5 W radios. We calculate the maximum flows according to our SRRA formulation across a range of dispersion factors and then calculate total network throughput. With all radios set to the same power, the total network throughput is higher for the TL BOI across all dispersion factors, shown in Figure 17.

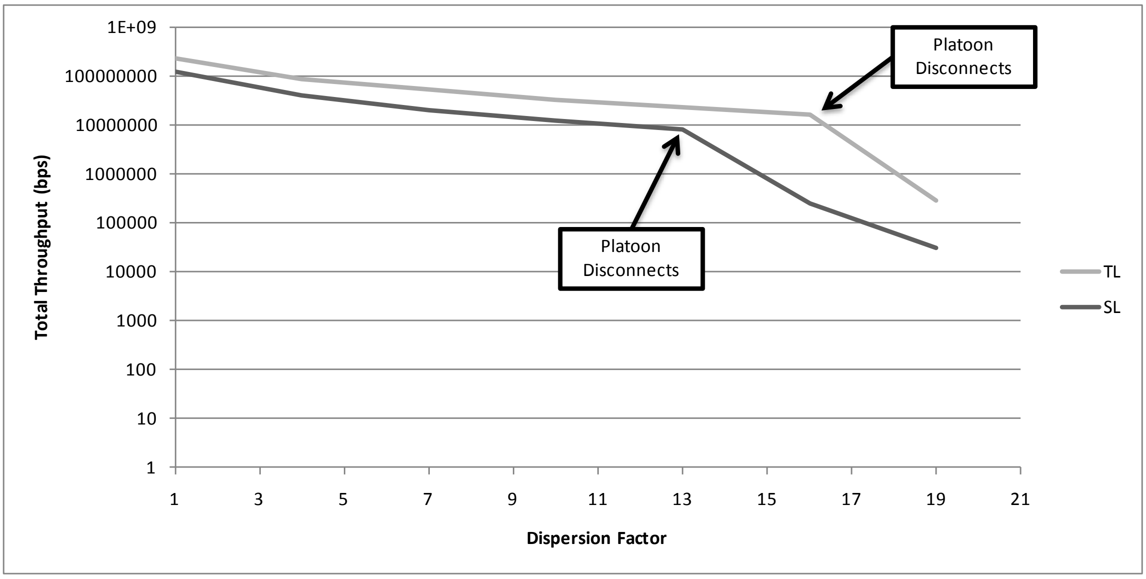


Figure 17. Total network throughput–homogeneous case (5 W).

This behavior is intuitive; one would expect that with more nodes in the network, a higher total throughput would be possible simply due to the significantly higher number of links present. As the dispersion factor increases, and received signal strength decreases, we see a decline in total throughput. The sudden drops in total throughput occur when one platoon loses connectivity with another. This happens for both the SL BOI and the TL BOI, but at different dispersion factors. The higher total throughput values for the TL BOI are the result of the TL nodes acting to relay traffic back to their respective platoons, maintaining interplatoon connectivity at greater ranges.

Next, we revisit the heterogeneous case involving 100 W and 5 W radios. Total throughput values, shown in Figure 18, demonstrate that the increase in the number of nodes in the TL BOI does not have a significant effect on total network throughput despite the greater number of links.

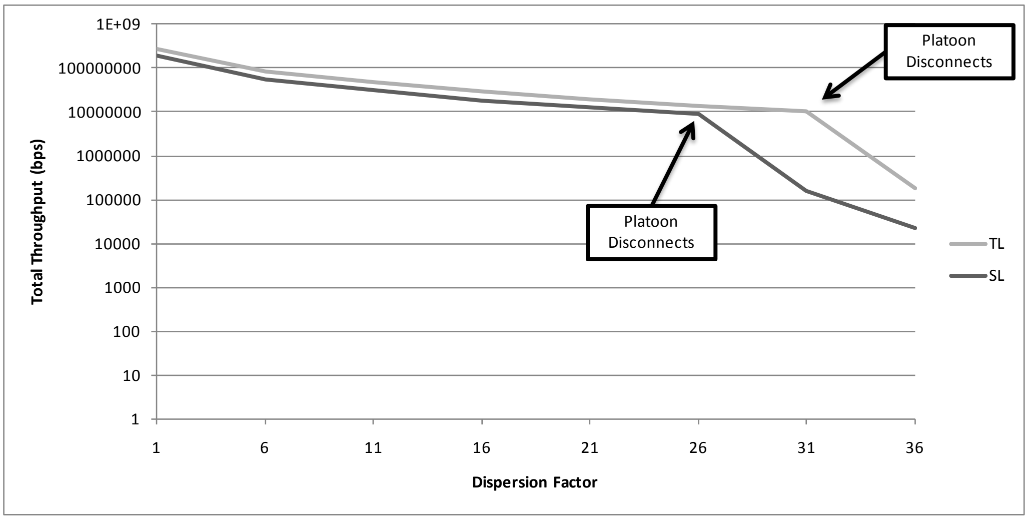


Figure 18. Total network throughput—heterogeneous case (100W, 5W).

The similarities in total throughput between bases of issue, shown in Figure 18, indicate that the benefits from peripheral nodes acting as relays are less noteworthy when high-power links dominate interplatoon connectivity.

The results of the Idealized SRRA Model indicate that increasing the number of nodes, as seen in the TL BOI, does not have any detrimental effects on total network throughput and, in some dispersion scenarios, serves to increase the total network throughput by providing relays to maintain connectivity between distant nodes. However, we have not measured the impact on the throughput associated with individual nodes. It is possible, and perhaps likely, that although the total traffic increases with the TL BOI, the individual nodes associated with the SL BOI actually receive reduced throughput, because they are "crowded out" by traffic from the team leaders.

B. STATIC END-TO-END TRAFFIC MODEL: DUPLEX NEEDLINES

While the idealized SRRA model provides an upper bound on network performance in the form of a generalized traffic model, practical applications more often call for the ability to route traffic between particular pairs of nodes. In the EPLRS system, these end-to-end connections take the form of *duplex needlines*.

Duplex needlines are constrained by a Relay Coverage constraint, which limits the number of allowable relays (hops) to a maximum of five. To understand how changes in the number of nodes affects the ability of radios to communicate on the network using duplex needlines, we present a model of static traffic demand. This model considers every pair of nodes and evaluates whether or not the network has available resources (i.e., node and link capacities) to support a duplex needline between them.

As occurs in an EPLRS network, we use a relay path-finding algorithm to determine the route for traffic through the network. This path is constrained by a Relay Coverage setting of five, and we restrict each RS to participating in a maximum of 32 needlines. We use Dijkstra's algorithm to find the shortest path, measured in terms of Euclidean distance, through the network while obeying the aforementioned constraints (Ahuja et al. 1993). The relay-path finding algorithm used by EPLRS is proprietary; however, our approach mimics its performance.

Using a static representation of the network, we assess how many simultaneous end-to-end connections are possible while operating within the confines of the relay coverage and needline constraints. To determine this, we first define a prioritized list of origin-destination (O-D) pairs. We base these priorities on the relative importance of each node within the network when placed into the context of an infantry company. Nodes representing higher echelons of the command structure have priority over lower ranking nodes. The result is an all-pairs list broken into three subgroups: connections between two high importance nodes, connections between a high importance node and a low importance node, and connections between two low importance nodes, as shown in Table 4.

We designate Platoon Leaders, Platoon Sergeants, and Squad Leaders as high importance nodes and Team Leaders as low importance nodes. Within each priority

Priority	**Group Make-Up**
1	High ↔ High
2	High ↔ Low
3	Low ↔ Low

Table 4. Point-to-point priorities.

group, we select O-D pairs at random. (This designation affects the input data to our analysis, but not the process. We can easily change the priorities and resolve, although this may yield different results.) We obtain a list of 1722 point-to-point connections in the TL BOI and 306 connections in the SL BOI. A simplified explanation is shown in Figure 19.

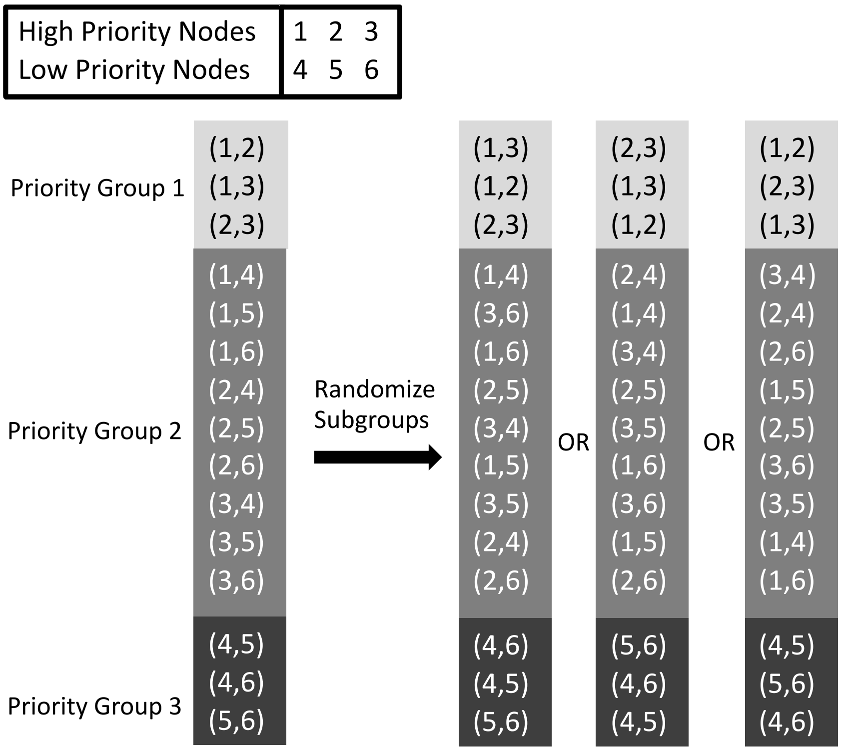


Figure 19. Example of demand list construction. We randomize the order of each origin-destination pair within each subgroup.

Following this list, we add end-to-end connections one at a time. For each O-D pair in turn, we determine the shortest path between them, and if this path also satisfies the relay coverage and needline constraints, the connection is a success. If not, the connection is a failure. We attempt each connection in the list in turn. Thus, we attempt all O-D connections in priority group 1 before those in priority 2, and we attempt all those within group 2 before attempting group 3. Figure 20 illustrates the results of this greedy allocation for two such lists.

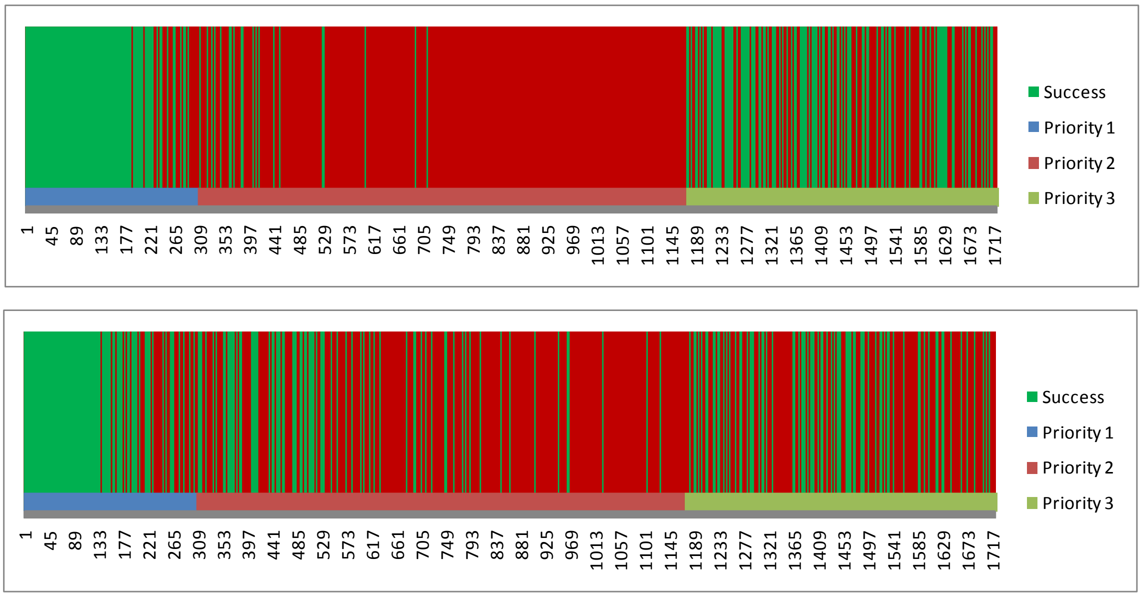


Figure 20. Results of greedy heuristic approach for two ranked lists.

Although this simultaneous demand for duplex needlines between all O-D pairs is unrealistic, this greedy algorithm gives us a conservative estimate of the percentage of total connections possible when constrained by the physics of wireless communications and EPLRS design characteristics. Furthermore, we can estimate the total number of simultaneous needlines possible for different dispersion factors, as shown in Figure 21.

In comparing the total number of end-to-end needlines to the total number of links for the same dispersion factors (in Figure 12), we observe that these constraints—on duplex needline path length and on RS participation in needlines—have a signifi-

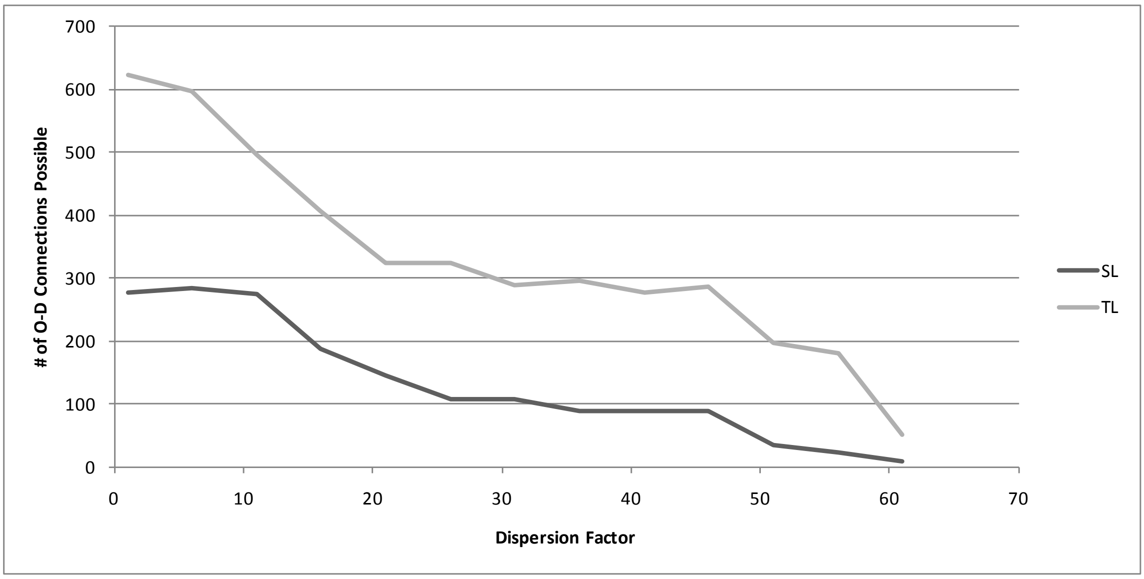


Figure 21. Number of duplex needlines (heterogeneous, 100 W and 5 W).

cant effect on the ability of the network to support end-to-end connections. We also observe that the TL BOI supports more duplex needlines than the SL BOI at all dispersion factors. But does this mean that all users in the SL BOI are better off?

Up to this point, this analysis assumes that end-to-end needlines are prioritized by group. We now consider what happens in the absence of this prioritization, that is, when we assign needlines randomly between all O-D pairs. In particular, we want to understand how the addition of nodes in the TL BOI can affect the number of high priority (Priority 1) needlines. Examining the number of duplex needlines possible at a particular dispersion factor for both a prioritized list and a random list, we see a significant decrease in Priority 1 needlines, as shown in Figure 22.

This decrease is a result of the lower priority O-D pairs "crowding out" the higher priority pairs. This trend is observable across a range of dispersion factors, shown in Figure 23. In that figure, the SL line represents the number of connections possible for the SL BOI, where we consider all connections Priority 1. We observe that O-D pairs in Priority 1 benefit from the larger BOI when needline allocation is prioritized, but that these same O-D pairs *suffer* from the larger BOI when needline

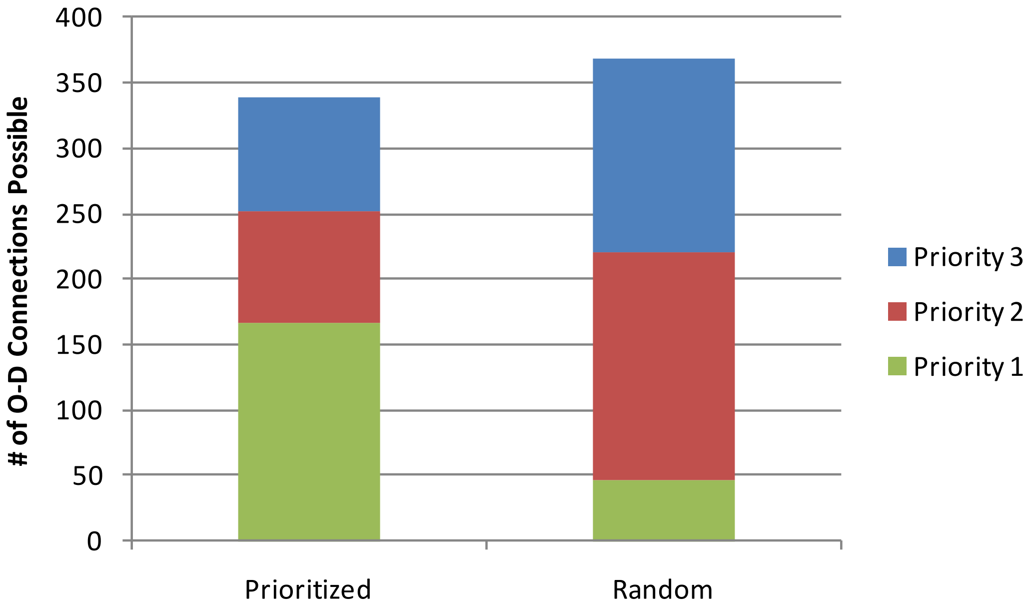
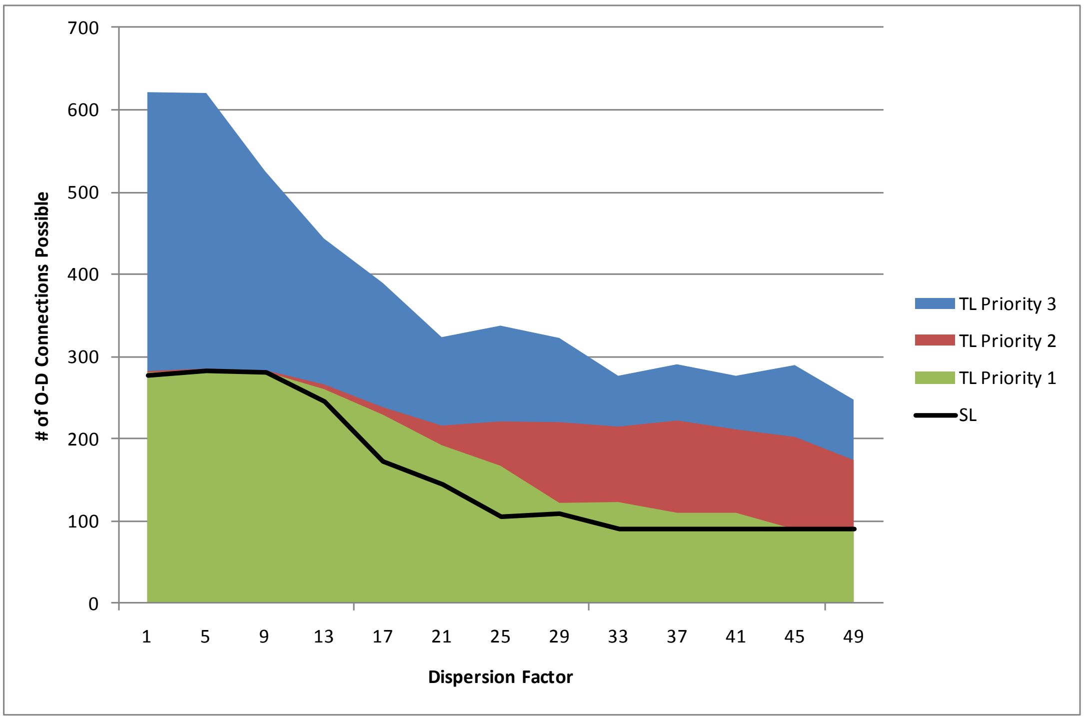


Figure 22. Effect of randomizing traffic demand (dispersion factor = 25).

allocation is not prioritized. Thus, *while a greater BOI results in a greater number of total needlines, the issue is which O-D pairs receive them.* The crowding of Priority 1 O-D pairs represents a possible degradation in network performance that could result from the increase in number of nodes. However, this effect can be mitigated by establishing policies for disciplined needline usage.



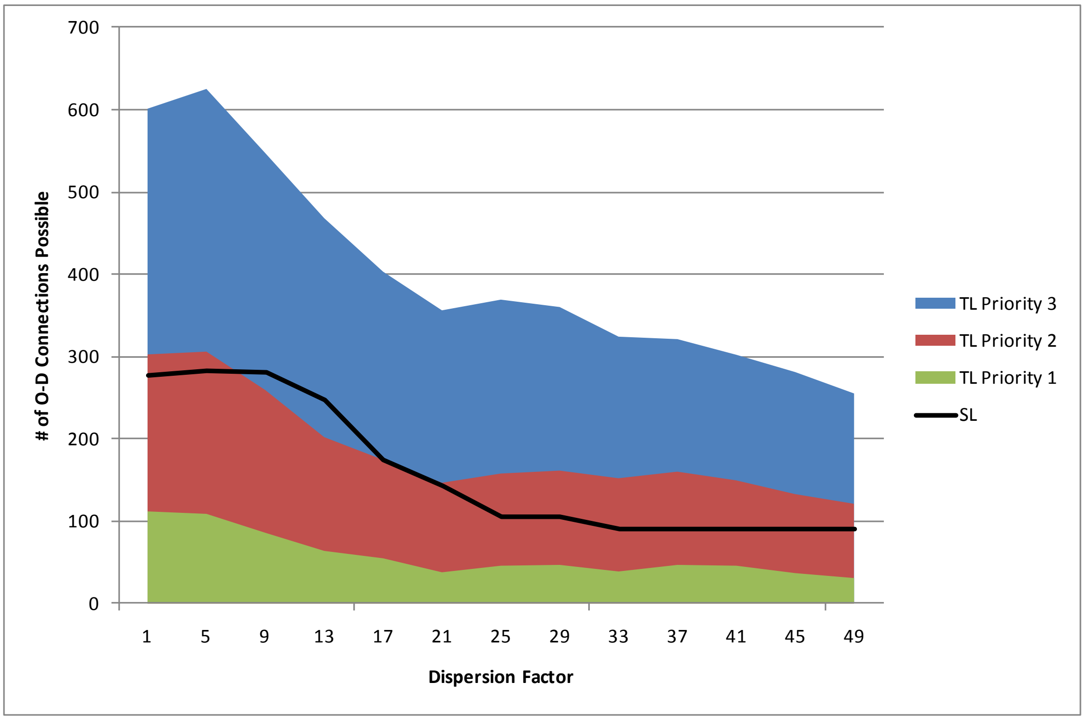


Figure 23. Top: number of duplex needlines by priority group for prioritized traffic. O-D pairs in Priority 1 benefit from the larger BOI when needline allocation is prioritized. Bottom: number of duplex needlines by priority group for random traffic. O-D pairs in Priority Group 1 suffer from the larger BOI when needline allocation is not prioritized.

C. MULTICAST COMMUNICATIONS: POSITION UPDATE MESSAGE MODEL

In this section, we consider multicast (i.e., one-to-many) communications, which are used primarily to pass location information in the form of "heartbeat" messages necessary to maintain situational awareness. RSs periodically transmit position-update messages that are broadcast over the network, providing each user with a common operating picture of the battle space. The periodicity of these messages is based on the node type and is a function of both time and movement. Nodes transmit position-update messages according to user defined time and motion filters. Time and distance intervals are node-specific to account for relative speeds of units and frequency of changes in position, shown in Table 5.

Node Type	Time Filter	Motion Filter
Auxiliary ground unit	1–600 seconds	10–400 meters
Manpack unit	1–600 seconds	10–100 meters
Surface vehicle	1–500 seconds	50–200 meters
Airborne rotary-wing unit	1–64 seconds	100–2,000 meters
Airborne fixed-wing unit	1–64 seconds	100–2,000 meters

Table 5. EPLRS position update filters (From CECOM, 2005).

Intuitively, one expects that increasing the number of RSs also increases the number of position-update messages transmitted across the network. We want to understand how, if at all, increasing the number of RSs can degrade the position reporting functionality of EPLRS.

Because these heartbeat messages share a common frequency, EPLRS implements a Carrier Sense Multiple Access With Collision Avoidance (CSMA-CA) multiple access method. Given the discrete nature of timeslots in a time-division system, CSMA-CA acts to reduce traffic collisions that occur when two RSs attempt to transmit in the same timeslot. The basic idea of CSMA-CA is that each RS on the network "listens" to the channel when it is not transmitting. Before the RS attempts to transmit, it determines whether the channel is already in use by another RS or if it is idle. If the RS senses the channel is idle, it will begin transmitting in the next timeslot assigned to the needline. If the channel is busy, the RS will wait a random number of timeslots before attempting to transmit again. The random "backoff times" help to reduce the number of collisions that occur when there are multiple RSs waiting to transmit. If every RS attempted to transmit in the first available idle timeslot, collisions would be much more likely to occur.

We can use discrete-event simulation to estimate the number of RSs it takes to overwhelm the system. The discrete event simulation replicates CSMA-CA behavior by scheduling position-update messages at specified intervals and then attempting to "send" them in their scheduled time step. We assume each time step is long enough for the message to traverse the network up to the Relay Coverage limit. If the needline is idle when a scheduled transmission comes up, the state of the needline becomes busy and we record a successful transmission. If the state is busy, we insert a randomly generated delay and, following that delay, we attempt transmission again.

The overall rate at which the network receives new heartbeat messages to broadcast is a product of the total number of radios and the time interval (or equivalently, the rate) at which each radio broadcasts. We expect that if the transmit interval is too short or the number of nodes too large, the ability of the system to support that situational awareness traffic could be degraded.

For a given number of radios and a given time interval between position-update messages, we can simulate the multicast behavior of the network. A transmission attempt is a success if the circuit is idle when the attempt is made. We can use the fraction of successful heartbeat transmissions as an estimate of the probability of successfully sending a message. By varying the the number of nodes and the interval between transmission attempts, we assess the potential for network saturation.

We assume a nominal value of 30 seconds for the transmission interval. We assume that each time step in the simulation is long enough to allow the full relay distance to be traversed, we conservatively assume each time step corresponds to 20 milliseconds of real time. Converting the 30-second interval into the corresponding number of time steps results in a transmission attempt every 1,500 time steps.

We evaluate CSMA network performance for varying numbers of nodes, shown in Figure 24. The results of the simulation highlight the decrease in the percentage of successful message deliveries. The sudden drop at approximately 190 nodes corresponds to the saturation point of the network.

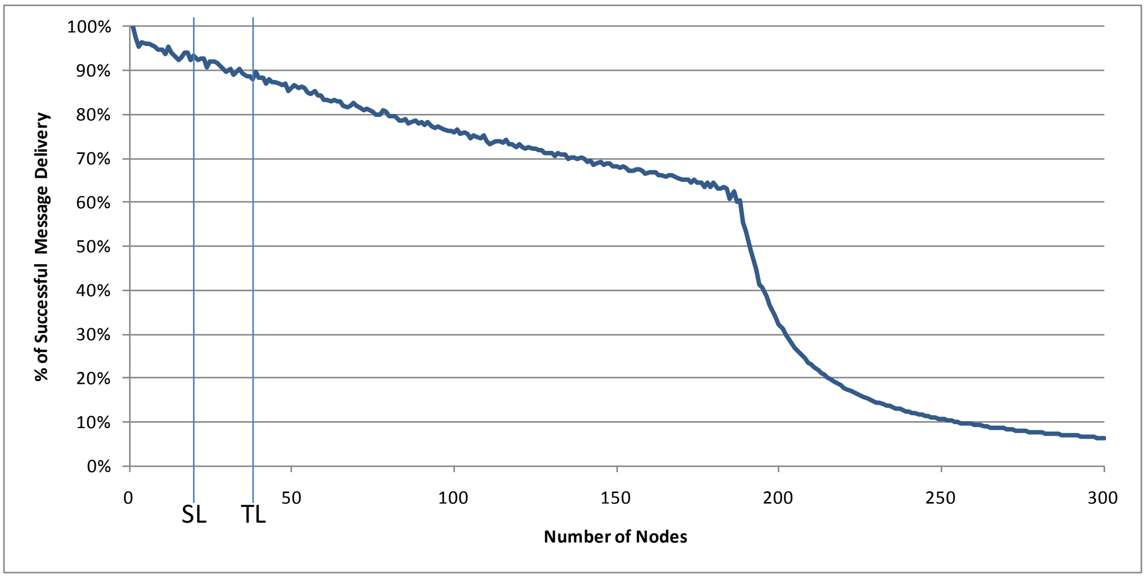


Figure 24. Percent of successful position-update message deliveries (30-second interval). At this interval, both BOIs are well below the saturation point.

The bases of issue under consideration deal with the deployment of 18 and 42 RSs for the SL and TL BOI, respectively. Assuming a 30-second interval between position messages, the increased number of nodes does not significantly affect the success rate for the bases of issue under consideration. However, if we decrease the interval to 5 seconds, we see that the network becomes saturated at a much lower number of nodes, shown in Figure 25. In this case, we observe that the TL BOI could suffer congestion collapse, while the SL BOI would not.

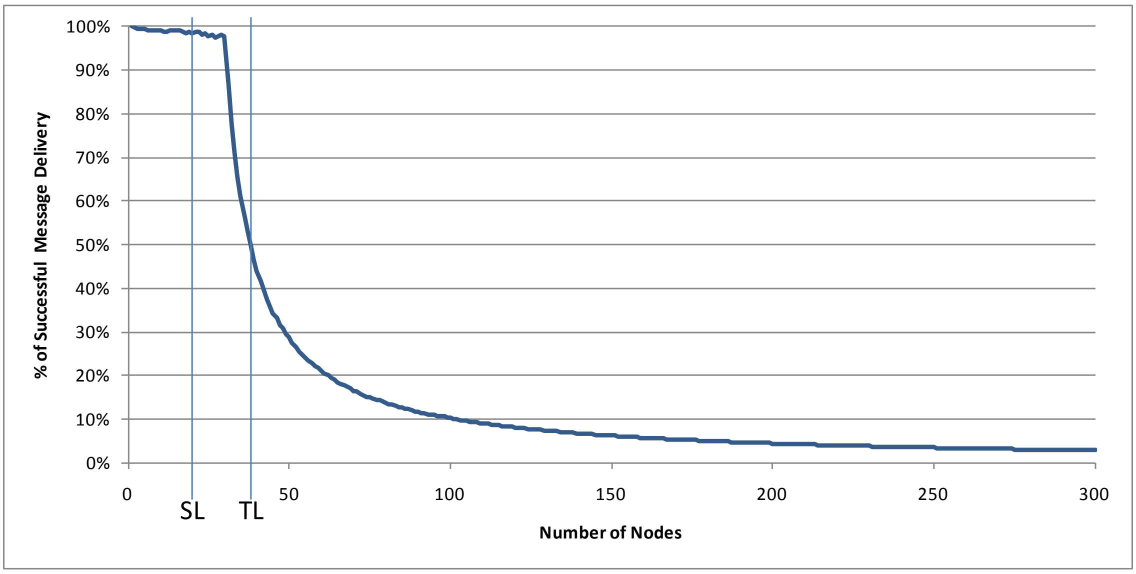


Figure 25. Percent of successful position update message deliveries (5-second interval). At this interval, the TL BOI is above saturation.

It is important to keep in mind that this scenario refers to users on a single CSMA needline. If a future deployment scenario needs to field a significantly greater number of RSs, the saturation effect could be mitigated by increasing the intervals between transmission attempts or establishing subnetworks to reduce the potential for collisions.

D. CHAPTER SUMMARY

In this chapter, we evaluate network performance using several different metrics under a variety of deployment scenarios. We use a physics-based approach to model wireless network behavior while maintaining applicability to EPLRS by accounting for its particular system characteristics. The goal is to represent EPLRS operation realistically enough to assess simple deployment tradeoffs, such as the impact of increasing the total number of wireless radios.

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IV. CONCLUSIONS AND FUTURE WORK

This research presents several mathematical models intended to address fundamental tradeoffs in the deployment of and operation of wireless ad-hoc networks. We focus specifically on networks using EPLRS radio technology, with the objective of understanding how the deployment of more radios affects the behavior and performance of the network. Integrating our analysis of network behavior, we summarize our answers to the basic question: *Does fielding more radios help?*

- Increasing the number of radios helps to increase the distances (dispersions) over which the network as a whole stays connected. However, the resulting end-to-end paths that maintain connectivity at larger distances have longer path lengths, measured in hops, and limitations in EPLRS may preclude their use. This is true both for low-powered and high-powered radios. Thus, *the overall benefit from additional radios on network connectivity may be marginal.*
- In contrast, *the use of higher-powered radios for either BOI does have significant improvement on the overall connectivity of the network.* Of course, higher-powered radios have their own limitations in terms of mobility and battery life, which are not addressed here.
- *Increasing the number of radios increases the total throughput capacity of the network,* as computed using the SRRA formulation and assuming uniform, but prioritized, traffic demand. Although the total network traffic increases with additional radios, we do not assert anything about whether individual radios observe an increase in traffic.
- Increasing the number of radios increases the total number of duplex needlines that the network can support. If the network maintains priority in establishing needlines, then high-priority O-D pairs stand to benefit from the increased deployment of radios. However, in the absence of this prioritization, highprioity O-D pairs can be crowded out by lower-priority O-D pairs.
- Increasing the number of radios has the potential to saturate the network's ability to broadcast position update messages. Specifically, the simple increase from 18 RSs in the SL BOI to 42 RSs in the TL BOI during periods of frequent broadcast (every 5 seconds per node), could result in congestion collapse on a single CSMA needline. However, this can be avoided by dedicating additional network resources to this task.

Overall, we observe that having more radios can improve the communications capabilities within a company under certain dispersion conditions. Total network throughput is higher, more point-to-point connections are possible, and overall situational awareness is improved through the use of position-update messages.

However, effective network management is a primary factor in determining network performance given an increase in node density. Poor network planning and undisciplined use can result in degraded support for duplex needlines and position-update message delivery. In the case of duplex needlines, the absence of prioritization results in some needlines getting crowded out, reducing the ability to establish high-priority links. This effect can be mitigated by the development of usage policies that favor high-priority traffic. For position-update messages, overly frequent transmissions can negatively affect the position reporting functionality of a large network. This can be mitigated through the appropriate selection of position-update message intervals for the size of the network.

The focus of this research is on comparing network performance in the bases of issue under consideration. Factors such as cost, training, weight, power requirements, and system availability are not explicitly considered in this study, but are important in the final BOI determination. Based solely on the network performance factors considered here, we find no reason to reject the TL BOI.

A. EXTENDING THIS ANALYSIS

There are a number of ways that the research in this report could be strengthened and/or augmented.

- *Account for Terrain Effects in TIREM.* The current analysis of network topology assumes flat terrain. A more realistic assessment would take advantage of the capabilities of TIREM to evaluate network performance for a specific geographic area by evaluating received signal strength over a terrain profile. This would provide an accurate representation of how the network functions in various terrain situations.

- *Validate Our Models With Real-World Data.* The results of this study could be evaluated for accuracy through the collection of real-world received signal strength and system usage data for deployed EPLRS networks. This would provide not only validation for the existing models, but could also inform the development of a demand model that more accurately represents real-world system employment.
- *Consider Needline Demands Over Time.* Our model of duplex needline communications relies on a greedy heuristic to determine needline capacity within the network. A more dynamic approach could use a queuing model to represent the arrival and duration of duplex needline requests. Combined with a more accurate model of needline demand, this would greatly improve understanding of needline requirements and system capacity.
- *Develop a More Realistic Position-Update Message Model.* A more accurate model would account for the fact that position-update information is constantly changing and would implement a "time to live" for each message vice attempting to send the same message until it succeeds. Also, instead of assuming that each blocked transmission attempt is a failure, an alternative approach would be to consider each completed message as a success regardless of how many times it had been blocked. Finally, the results of this model could be mapped to an actual performance metric, such as mean squared error, in estimating node position.
- *Examine Various Dispersion Scenarios.* This study implements a particular dispersion model to describe node positions. Use of alternative models could improve the validity of the model results for specific deployments. For example, a more realistic scenario could constrain node locations to an existing road network, resulting in very different network topologies.

B. RECOMMENDATIONS FOR FUTURE WORK

This work has examined a particular communication system (EPLRS) under a number of notional scenarios and has provided recommendations regarding a basis of issue of RSs. Perhaps more importantly, this work has highlighted a number of shortcomings in the current framework in which wireless communication systems are evaluated.

We have evaluated the performance of an EPLRS system under a number of generic scenarios, which allow us to make general conclusions about the performance on the system in various circumstances. However, more realistic scenarios would allow us to draw conclusions about the performance of hypothetical systems in actual mission-relevant circumstances.

Recommendation 1 *We recommend that future research efforts identify a set of "canonical missions" for evaluating communication systems.*

Each of these missions might be defined in terms of:

- *Specific demands for network traffic* between individual nodes, based on their role in the mission.
- *Potentially novel dispersion models* that reflect the relative position of nodes during different missions, or perhaps, different phases of the same mission.
- *Characteristic terrain.* Our assumption of zero elevation provides a best-case analysis in terms of received signal strength. In practice, environments with elevation change will result in degraded network performance.

For example, our use of TIREM to evaluate received signal strength implicitly assumes that man-made structures and vegetation are not significant. *While the basic structure of our analysis applies generally, we anticipate that considerable changes to the individual models, such as the dispersion model and signal propagation model, would need to be made to handle specific missions, such as in urban environments.*

Likewise, while we have identified a set of generic performance metrics relevant to EPLRS operation, our metrics are far from definitive.

Recommendation 2 *We recommend that future research also attempt to identify a mapping between measurable network performance and mission assurance.*

Network engineers have developed sophisticated techniques to measure, simulate, and emulate network traffic at increasing levels of precision. Yet, what we can measure and simulate does not directly inform the likelihood that a military unit will succeed in their mission. We anticipate that some simple metrics, such as network availability, will be broadly applicable to a variety of deployment scenarios, but that others may be mission-specific. As part of this, we recommend that efforts be directed to identify what additional data (if any) should be collected in order to best evaluate the performance of wireless communication systems.

In conclusion, the growing demand for real-time information on the battlefield will assure the continued importance of wireless networks in military operations. As technology advances, so does our need to assess tradeoffs in the deployment, configuration, and use of these communication systems. While the ultimate validation of such systems remains on the battlefield, there is considerable insight to be gained from basic research directed at reducing the guesswork and/or trial-and-error in ad-hoc deployment.

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