Simulation and Analysis of Mobile Ad hoc Network Technology in the US Marine Corps Infantry Battalion

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ABSTRACT

A mobile ad hoc network (MANET) is an autonomous communications system of mobile nodes equipped with radio transmitters and receivers. This research explores three critical challenges faced by communications planners in employing MANET technology within the US Marine Corps infantry battalion. First, we examine and quantify the ability of MANETs to support communications between highly mobile units operating in potentially rugged terrain over long distances with relatively low-power radios. We also analyze the ability of MANETs to use intermediate nodes to overcome the inherent range limitations of higher frequencies. Finally, we consider the challenge of allocating bandwidth to MANET systems to enable sufficient throughput rates. To explore these challenges, we conduct a rigorous comparative analysis using various network simulation and optimization techniques. We develop a network formulation to model key aspects of communications systems, and then simulate and gauge network performance in environments ranging from low-fidelity, theoretical representations to realistic, high-fidelity combat scenarios.

We quantify the benefit that MANETs can provide to tactical communications networks over traditional point-to-point networks. We also quantify the value of the use of unmanned aircraft systems (UASs) as airborne nodes in MANETs, a capability especially useful in communications scenarios involving rugged terrain and large distances. We also find that due to MANET fragility in high-loss environments, tactics may need to be modified to support the full use of MANET communications. To our knowledge, we are the first to rigorously examine and quantify the value of MANET technology within the Marine Corps infantry battalion.

INTRODUCTION

Description of Problem

Tactical forces within the US Marine Corps (USMC) are becoming increasingly dependent on the rapid, reliable transfer of information throughout the battlespace. *Marine Corps Vision and Strategy 2025* (USMC, 2008) states "the Marine Corps will integrate C2 [command and control] and ISR [intelligence, surveillance, and reconnaissance] capabilities down to the squad level," and "we will aggressively pursue integrated microtechnologies, such as a secure communications personal data apparatus that communicates via the spoken word, data, and imagery." The Marine Corps document *A Concept for Enhanced Company Operations* (2008) emphasizes "support to highly mobile forces with on-the-move/over-the-horizon communications for disparate tactical nodes," and states to achieve this, "tactical units must gravitate from push-to-talk radio systems to mobile ad-hoc mesh networking."

A mobile ad hoc network (MANET) is an autonomous communications system of mobile nodes equipped with radio transmitters and receivers. These nodes may move and connect in wireless, dynamic, multihop topologies, and exhibit self-learning, self-healing behavior (Corson and Macker, 1999; Aggelou, 2005)—that is, individual nodes may automatically connect and disconnect from a MANET without any user interaction. A MANET system comprises physical radios and the associated networking protocols, waveforms, and modulation schemes. We assume all nodes within a MANET can serve as the source and/or destination of communications traffic, and can function as intermediate nodes to route communications traffic from source to destination. MANET nodes may physically connect to client devices (such as laptops), or serve as user terminals themselves. In this way, MANETs are similar to client mesh wireless mesh networks (WMNs) (Zhang et al., 2006, pp. 564–567), where client devices perform routing functions.

Existing tactical radio systems within the USMC infantry battalion include the Single Channel Ground and Airborne Radio System (SINCGARS) and various other radios operating in the high frequency (HF), very high frequency (VHF), and ultra-high frequency (UHF) ranges. In contrast to MANETs, these existing systems can function only as point-to-point (PTP) networks: that is, nodes must communicate directly and cannot function as intermediate nodes (Hong et al., 1999). Although some radio systems allow nodes to function as retransmitters, in such a configuration nodes are simply rebroadcasting received traffic and not operating as part of a MANET.

The Marine Corps is currently developing, purchasing, and fielding new radio devices capable of forming MANETs to connect widely dispersed nodes with data communications capabilities. These systems include the PRC-117G wideband multiband tactical radio, radios belonging to the (now defunded) Joint Tactical Radio System (JTRS) family, the Expeditionary Communications (EXCOMM) vehicle, and others (Harris Corporation, 2011; Marine Corps Systems Command, 2011). Yet, the service has not extensively studied the tactical considerations of the use of MANET architectures versus traditional tactical architectures, nor the most effective employment of these systems in a tactical environment.

This research explores three critical challenges faced by communications planners in employing MANET technology within the USMC infantry battalion. First, tactical forces are increasingly operating in a geographically separated manner. Such dispersed units require communications networks able to dynamically overcome the challenges of wirelessly connecting highly mobile units operating in potentially rugged terrain over long distances with relatively low-power radios (Goulding, 2009). We examine and quantify the ability of MANETs to support operations in these demanding environments.

Communications planners must also consider the challenges of signal attenuation. MANETs typically operate at higher radio frequencies (RFs) than traditional PTP networks. These higher frequencies enable greater throughput rates, but in general are subject to greater signal attenuation than lower frequencies, and will thus propagate a shorter distance (all other things being equal) (Singal, 2010, pp. 37–39). However, unlike traditional PTP networks, MANETs may use intermediate nodes to relay traffic. We analyze the ability of MANETs to use intermediate nodes to overcome the inherent range limitations of higher frequencies.

Finally, we consider the challenge of allocating bandwidth to MANET systems to enable sufficient throughput rates. The throughput capacity of a wireless link is a function of both bandwidth and received signal strength (RSS) (Shannon, 1949). Bandwidth is the range of the RF spectrum allocated for use in Hertz (Hz), and RSS is the RF power of the received signal, as measured at the receiver in dBm or watts. Since MANET systems typically operate at higher frequencies and are thus subject to greater signal attenuation, greater bandwidth is required for MANET systems to provide throughput rates equal to lower-frequency systems. We examine and compare the bandwidth requirements for lower-frequency PTP systems and higher-frequency MANET systems.

To explore these challenges, we conduct a comparative analysis using network simulation and optimization techniques to evaluate several MANET architectures against a base case consisting of traditional PTP network technology (i.e., currently fielded technology as of fiscal year 2011). We first develop a network formulation to model key aspects of traditional PTP and MANET systems. We then simulate and gauge network performance in environments ranging from low-fidelity, theoretical representations to realistic, high-fidelity combat scenarios. This systematic approach enables us to examine fundamental properties of MANET and build intuition with theoretical techniques before using less tractable, higher-fidelity simulations.

We quantify the benefit that MANETs can provide to tactical communications networks over traditional point-to-point networks. We also quantify the value of the use of unmanned aircraft systems (UASs) as airborne nodes in MANETs, a capability especially useful in communications scenarios involving rugged terrain and large distances. We find that due to MANET fragility in high-loss environments, small unit tactics may need to be modified if commanders wish to fully utilize the advantages offered by MANET communications.

To our knowledge, we are the first to rigorously examine and quantify the value of MANET technology within the USMC infantry battalion. Our work has been used by the study sponsor, the Marine Corps Tactical Systems Support Agency (MCTSSA), in improving the fidelity and rigor of MANET test and evaluation efforts.

Previous Work

Coyne et al. (2007) use a human-factors based assessment to identify the optimal set of communications gear to support Marines conducting distributed operations (DO). They identify a list of information that must be exchanged in order to execute tactical tasks, and methods (visual, auditory, etc.) of exchanging that information. Their recommendations are based solely on subject matter expert (SME) input; they do not conduct any simulation or testing to validate their conclusions.

Extensive field testing has been conducted to demonstrate the ability of MANETs to support geographically dispersed tactical combat operations, including Bommer (2007) and by the Marine Corps Warfighting Laboratory (Reynolds, 2011). Simmons and Curran (2007) consider the benefits of MANET to a USMC platoon operating in a geographically dispersed manner by examining the results of previous field testing. Much of this research incorporates simulation. However, none specifically considers the impact of MANET technology on each tier within the battalion.

Blackshear (2002), Kioumourtzis (2005), and Smith (2009) use computer simulation to compare various routing protocols within a MANET, including UAS nodes. Kant et al. (2008) use optimization to calculate network capacity in MANETs. Karhima et al. (2005) use computer simulation to evaluate MANETs in the presence of mobile jammers. However, none consider networks capable of supporting a battalion, nor do they consider the effects of mobile nodes operating over rugged terrain.

Alderson et al. (2011b) examine the tradeoffs inherent in the fielding of MANET radios, specifically the Enhanced Position Location Reporting System (EPLRS). To model network performance, they use first principles-based models and discrete event simulation, including the Simultaneous Routing and Resource Allocation (SRRA) problem of Xiao et al. (2004). They find that while a small increase in the number of nodes does not necessarily have a detrimental impact on network performance, larger networks are more difficult to properly manage. We also use SRRA to model network performance, and our research builds on their concept of network dispersion (i.e., a model of the relative dispersion between nodes).

Much of the research presented in this paper was conducted as part of the Reinforced Infantry Battalion MANET Study, executed by the Marine Corps Combat Development Command (MCCDC) and sponsored by MCTSSA. See MCCDC (2011) for the complete study report.

This paper is organized as follows. In the next section, we describe in detail our techniques for modeling tactical communications networks, and the methods we use to measure the performance of our models. We describe several analyses using these models, and then briefly summarize our findings. We conclude with suggestions for follow-on research.

COMMUNICATIONS NETWORK MODEL

Infantry Battalion Network Structure

We create a mathematical network model to simulate key aspects of an infantry battalion communications network. A Marine Corps reinforced infantry battalion consists of approximately 700 Marines, typically assigned to three infantry companies, a weapons company, and other attached units such as an amphibious vehicle platoon or engineer platoon. Due to simulation constraints, we model only the leaders at each tier of the battalion. These tiers are the battalion, company, platoon, squad, and fire team, and the respective leaders are the battalion commander, company commanders, platoon commanders, squad leaders, and fire team leaders (see Figure 1). Note each tier except the fire team tier has three identical subcomponents; for example, each company has three platoons, each platoon has three squads, and so on (we assume that Weapons Company personnel are divided among the other battalion elements). As dictated by scenario, we also model air- and seaborne radios and the Fire Support Coordination Center (FSCC) as company-level leaders. Each tier may use different types of radios (and thus use different transmission powers, frequencies, etc.), but we assume all nodes at a particular tier will use the same type of radio.

Modeling Network Topology

We define each leader within the battalion as a node within our network model, and define

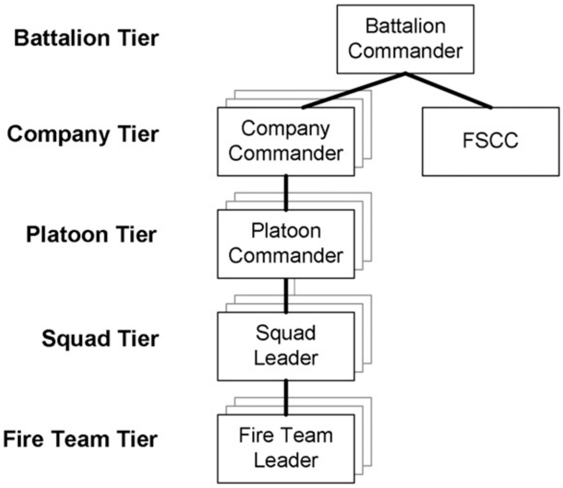

Figure 1. A simplified infantry battalion hierarchy. Each node except the fire team leader may have three identical sub-components. Such a battalion has a total of three companies, nine platoons, 27 squad leaders, and 81 fire team leaders.

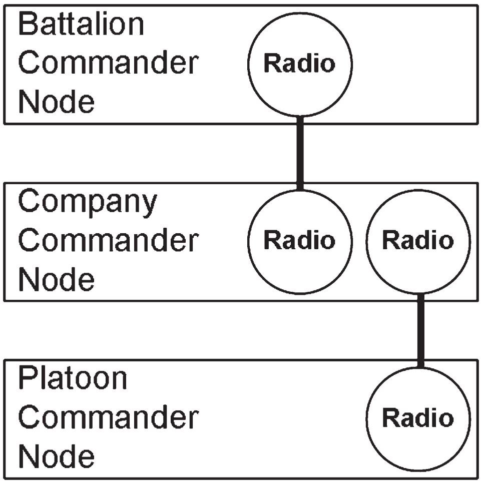

Figure 2. Example of the connections between three nodes. Each node may have more than one radio (e.g., the company commander node), but nodes connect to other nodes using only one radio.

N to be the set of all nodes, indexed by $i = 1, 2, \ldots, n$, where $n = |N|$. Our scenarios model between 40 and 121 nodes, depending on the number of personnel and vehicles modeled in each scenario. Nodes connect via wireless links or arcs, denoted $(i, j) \in A$. We distinguish these point-to-point arcs from source-destination pairs $(u, v) \in D \subset A$, which are two nodes within the battalion that must exchange communications traffic. In the base case (consisting of contemporary PTP technology), no node can serve as an intermediate node, and nodes exchange traffic only with their immediate seniors and subordinates (e.g., a company commander will only exchange traffic with his battalion commander and his platoon commanders). In the MANET cases, we assume the same source-destination pairs D must communicate, but certain types of radios may serve as intermediate nodes.

A single node may represent one or more man-packed, vehicular, or airborne radios. However, a node in any arc can connect to the distant node using only one fixed radio (i.e., a node may not dynamically connect using a different radio). See Figure 2 for a simple example. Each node (battalion, company, and platoon commander) communicates to other nodes using only one radio, but the company commander node communicates using two different radios. We model the characteristics of each radio via different arc capacities (see following sections).

To simulate various network routing configurations, we describe several MANET types by defining different arc sets A. A_{PTP} includes only PTP connections. A_{Direct} allows MANET-capable radios to connect with other MANET-capable radios only in a node's direct chain of command. A_{Total} allows all MANET-capable radios to connect, regardless of chain-of-command assignment. A simple example is presented in Figure 3. A platoon commander must exchange communications traffic with the company commander. Using A_{PTP}, the platoon commander

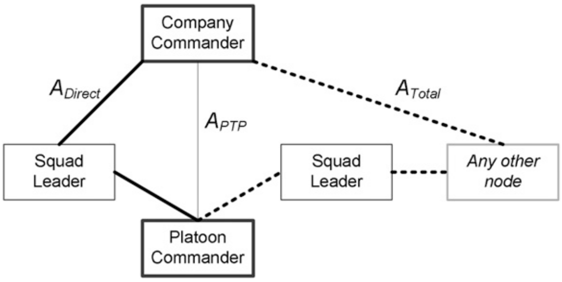

Figure 3. Example of the three routing types, A_{PTP}, A_{Direct}, and A_{Total}.

can only communicate directly with the company commander (thin black line). With A_{Direct}, the platoon commander can route traffic through other nodes, such as a squad leader, in his direct chain of command (heavy black line). With A_{Total}, traffic can be routed through any number of other nodes serving as intermediate nodes (dashed line).

Calculating Network Availability

One of our measures of network performance is network availability, defined as the number of source-destination pairs $(u, v) \in D$ that can successfully exchange traffic. Network availability is arguably the most important measure of network performance because without it, no nodes can communicate. By simply counting nodes, we implicitly assume each node generates traffic with the same relative value. This is unrealistic, as the battalion commander's traffic will generally be more important than any other traffic, and there are instances when a low-tier node could generate very important traffic (e.g., while calling in artillery reports). However, objective traffic value data do not exist, and this assumption allows us to obtain generalized results.

To calculate network availability, we first determine which nodes $(i, j) \in A$ are connected wirelessly by calculating the signal-to-noise (SNR) ratio. We assume the environment contains white noise that is constant as a function of time. If the SNR is above the technical threshold for the radios in question in both directions, the two nodes are connected. To determine the signal component of the SNR ratio, we calculate the RSS ρ_{ij} between each node in dBm using the standard link budget formula (Olexa, 2005, p. 79):

$$\rho_{ij} = power_i + g_i - l_i - l_{path} - l_{misc} + g_j - l_j \quad (1)$$

where $power_i$ is transmitted power in dBm, g_i and g_j are respectively the gains of the nodes i and j in dB, l_i and l_j are respectively the losses (i.e., from cables, connectors, etc.) of the nodes in dB, l_{path} is total path loss in dB, and l_{misc} is miscellaneous loss (such as fade margin) in dB. All of the terms in Equation (1) are input data, determined by the equipment and environment, except for the total path loss l_{path}, which depends on the physical position of nodes i and j and the intervening terrain.

Our formulation allows the use of any method for computing l_{path}, including the Irregular Terrain Model (ITM) (Longley and Rice, 1968) and Hata-COST 231 (COST, 1999). We prefer the Terrain Integrated Rough Earth Model (TIREM) of Alion Science & Technology Corporation (Alion, 2007). This model samples terrain elevation to compute path loss, and considers the effects of free space loss, diffraction around obstacles, and atmospheric absorption and reflection.

We assume source-destination pairs $(u, v) \in D$ can successfully exchange traffic if a path consisting of connected arcs exists from node u to node v, and from node v to node u. To determine if paths exist between all source-destination pairs $(u, v) \in D$, we solve the all-pairs shortest path problem using the Floyd-Warshall algorithm (Floyd, 1962; Warshall, 1962) where arc costs are inversely proportional to arc RSS. This approach favors both arcs with high RSS, and paths consisting of fewer arcs (or "hops"). Our model is similar to actual data network link state routing protocols, such as the Open Shortest Path First (OSPF) protocol (Moy, 1988; Aggelou, 2005).

Calculating Network Throughput

Our other metric of performance is network throughput, defined as the rate of traffic flow in bits per second (bps) between each source-destination pair $(u, v) \in D$. These pairs define the commodities in our multicommodity network flow problem (Ahuja et al., 1993). We use the term "traffic flow" to refer generically to the transmission of packets or datagrams during a data session. We adopt and modify the simultaneous routing and resource allocation (SRRA) problem of Xiao et al. (2004) to approximate network throughput. First, we calculate arc capacities (as opposed to arc costs calculated for the network availability metric) between each node using the Shannon capacity formula (1949), which establishes a theoretical upper bound on transmission capacity in bps. Following Xiao et al. (2004), the capacity from node i to node j is:

$$(Capacity)_{ij} = bandwidth\ \log_2\left(1+\frac{gain_{ij}}{noise_{ij}loss_{ij}}P_{ij}\right) \quad \forall(i,j)\in A \tag{2}$$

where *bandwidth* is channel bandwidth in Hertz, $gain_{ij}$ is the sum of the antilog gain terms (g_{ij} and g_{ji}), $noise_{ij}$ is the background noise power in watts or volt^2 from node i to node j, and $loss_{ij}$ is the sum of the antilog loss terms (l_{ij}, l_{ji}, l_{path}, and l_{misc}). These are input data calculated based on the position of the radios within the simulation environment. We assume each radio has limited total transmission power denoted p_i (in watts), and we define P_{ij} to be the amount of p_i used to transmit from i to j. Thus, each node is additionally constrained by

$$\sum_{j:(i,j)\in A} P_{ij} \le p_i. \tag{3}$$

We wish to measure traffic flow between each source-destination pair $(u,v)\in D$ in bps. We quantify the value of network flow using the log-utility function of Xiao et al. (2004). This function more equitably distributes flow than a linear function by assigning diminishing value to increasing flow. Note that a zero flow is assigned an infinite penalty, so there is strong incentive to assign some flow to each source-destination pair. Defining S_u^v to be the total flow originating at node u and destined for node v, we have

$$(Utility\ of\ Total\ Network\ Flow) \equiv \sum_u \sum_{v\neq u} \log_2(S_u^v). \tag{4}$$

Our version of the Xiao et al. (2004) SRRA problem follows:

Formulation SRRA

Index Use

$i\in N$	node (*alias j, k*)
$(i,j)\in A$	directed arc (*link*)
$(u)\in D\subset N$	destination (alias v)

Input Data

$gain_{ij}$	sum of antilog gain terms from $i\in N$ to $j\in N$	[none]
$loss_{ij}$	sum of antilog loss terms from $i\in N$ to $j\in N$	[none]
p_i	maximum total transmission power per node	[watts]
bandwidth	channel bandwidth	[hertz]
$noise_{ij}$	background noise power from $i\in N$ to $j\in N$	[watts]

Decision Variables

S_u^v	total flow of traffic from $u\in N$ to destination $v\in D$	[bps]
F_{ij}^v	traffic flow along arc $(i,j)\in A$ to destination $v\in D$	[bps]
T_{ij}	total flow along arc $(i,j)\in A$	[bps]
P_{ij}	total transmission power along arc $(i,j)\in A$	[watts]

Formulation

$$\max_{S,F,T,P} \sum_u \sum_{v\neq u} \log_2(S_u^v) \tag{S0}$$

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

$$T_{ij} = \sum_d F_{ij}^v \qquad \forall(i,j)\in A \tag{S2}$$

$$T_{ij} - bandwidth\ \log_2\left(1 + \frac{gain_{ij}}{noise_{ij} loss_{ij}} P_{ij}\right) \le 0 \qquad \forall (i,j) \in A \qquad \text{(S3)}$$

$$\sum_{j:(i,j)\in A} P_{ij} \le p_i \qquad \forall i \in N \qquad \text{(S4)}$$

$$S_u^v \ge 0 \qquad u \neq v \qquad \text{(S5)}$$

$$F_{ij}^v \ge 0 \qquad \forall (i,j) \in A, \forall v \in D \qquad \text{(S6)}$$

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

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

Given fixed node locations, this is a multicommodity network flow problem. The objective function (S0) maximizes the total utility of traffic flow between each source-destination pair. Constraints (S1) ensure balance of flow at each node. Constraints (S2) define the total flow along any arc as the sum of all traffic flows along that arc. Constraints (S3) ensure that total flow along each arc is less than or equal to its capacity. Constraints (S4) ensure that total transmission power at each node is conserved. Constraints (S5)-(S8) ensure nonnegativity.

As observed by Xiao et al. (2004), the SRRA problem has special structure that allows it to be solved via dual decomposition. Specifically, the dual function can be evaluated separately in the network flow variables *S*, *F*, *T*, and the communications variable *P*. Xiao et al. (2004) observe that the dual function is always convex. They assume that Slater's condition holds (see Boyd and Vandenberghe, 2004, Sec. 5.2)—that is, a feasible solution (*S*,*F*,*T*,*P*) exists such that the nonlinear capacity constraints hold with strict inequality. They conclude that strong duality holds and the solution to the primal problem is equal to the solution of the dual problem.

However, Xiao et al. (2004) also note that the objective function of the primal problem is not strictly concave in the variables *F* and *T*, and thus the dual function is only piecewise differentiable. As a result, the dual problem is a nondifferentiable convex optimization problem, to which they apply the subgradient method to obtain a solution. Each iteration of the subgradient method might not necessarily improve the dual objective value, but each iteration reduces the distance to the optimal solution (Bertsekas, 1999, p. 621). See Xiao et al. (2004), Shankar (2008), and Nicholas and Alderson (2013) for details on solving the SRRA problem.

We use the General Algebraic Modeling System (GAMS, 2011) and the CONOPT (2011) solver to solve the SRRA problem to near optimality. We use total delivered flow between each source destination pair S_u^v as a measure of network throughput. We calculate both network availability and network flow at each time step within the simulation. Our models of arc connections, source-destination paths, and throughput are useful simplifications of how actual radio links are established and maintained. These first-principles, physics-based models establish a performance upper bound, because ultimately no modulation scheme, waveform, protocol, or other characteristic can overcome the physical-layer limitations of radio physics.

ANALYSIS AND RESULTS

We use GAMS (GAMS, 2011), Microsoft Visual Basic for Applications (VBA) (Microsoft, 2011) and Analytical Graphics, Inc. (AGI) Satellite Toolkit (STK) (AGI, 2011) to simulate communications network topologies within both generic battalion formations on flat terrain, and within our realistic tactical scenarios. The three scenarios respectively model an amphibious assault, a mechanized movement to contact, and an irregular warfare operation, and include detailed node movement plans and terrain information. See MCCDC (2011) and Major Combat Operation−1 (2007) for complete details on our scenarios.

We conduct deterministic, simulation-based comparative analysis between the base case and several MANET cases. We model both theoretical radios and actual fielded and planned radio sets using technical specifications provided by the radio manufacturers and other subject matter experts. The base case consists of non-MANET radios operating in the low VHF range (65 MHz). In this paper, we consider only two MANET cases; they are based on actual radios but we withhold their nomenclature and exact specifications. The first (VHF MANET) consists of radios operating in the high VHF range (225 MHz), and the second (UHF MANET) consists of radios operating in the UHF range (1.125 GHz). See MCCDC (2011) for complete details on all of comparative cases.

Using network availability and throughput as a proxy for network performance, we measure network performance both overall and as a series of time-stepped instances at 1-minute intervals during our scenarios. We examine performance both for each tier of the infantry battalion (battalion, company, platoon, and squad), and for the entire battalion, on both theoretical flat terrain and across all three tactical scenarios, and using both theoretical and actual radio specifications. For the sake of brevity, the following sub-sections present our summarized analytic results by major findings. See MCCDC (2011) for complete results.

The Effect of the Ability to Route Traffic

Our first analysis considers the effects of the ability to route traffic on network availability. We model theoretical radios operating at 65 MHz and 10 watts of transmission power, and examine network availability for routing types A_{PTP}, A_{Direct}, and A_{Total}. Figure 4 presents the battalion network availability for the amphibious assault scenario as a function of time, results typical of all three scenarios.

In this scenario, a total of 26 landing craft, aircraft, and other vehicles transiting ashore communicate with the battalion commander located on a ship. The vertical axis depicts the number of nodes that are able to communicate with the battalion commander (i.e., network availability), and the horizontal axis depicts scenario time. The effects of the various assault waves are evident in the ‘‘No Mesh’’ line in Figure 4: the vehicles gradually move ashore up to time 05:30, then return to the ship at 06:00, and again go to the shore around 06:15.

We calculate average availability by averaging network availability at each time step over the course of the scenario. Without the ability to route traffic, the point-to-point network delivers an average battalion network

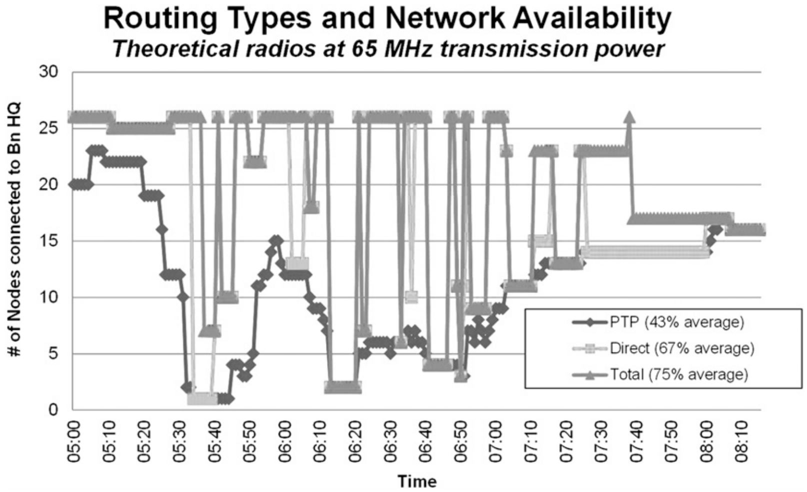

Figure 4. Battalion network availability during the amphibious assault scenario for three routing types.

availability of 43 percent—that is, on average 43 percent of the company-level units can successfully exchange traffic with the battalion commander. Networks with the ability to route traffic (routing types A_{Direct} and A_{Total}) provide much greater average network availability of 67 and 75 percent, respectively, because they are able to use intermediate nodes to route traffic between the ship and vehicles ashore. Note there are moments when the routable networks do not provide greater network availability; this occurs when there are limited or no intermediate nodes available for routing. Also, near the end of the scenario network availability does not go to zero because some of the assault vehicles return to the ship.

Figure 5 presents battalion network availability for all three scenarios, averaged over time for the three routing types. As with the amphibious assault scenario, we find that all other things being equal, the ability to route traffic can greatly increase network availability.

The Effect of Higher Frequencies

However, all other things are not typically equal. Perhaps the most significant physical-layer difference is that MANET radios generally operate at higher frequencies than PTP radios. These higher frequencies are subject to greater signal attenuation than lower frequencies (Singal, 2010). We next explore the ability of MANET radios to overcome this inherent disadvantage by routing traffic. We model theoretical A_{PTP} radios operating at 65 MHz, and MANET A_{Total} radios operating at both 200 MHz and 400 MHz. Figure 6 presents average battalion network availability for all three scenarios.

In the amphibious assault scenario, the ability to route traffic does not overcome the range limitations of higher frequencies, and neither routable network provides availability equal to the PTP network at 65 MHz. However, in the irregular warfare scenario, both the routable networks provide greater network availability than the PTP network. The 400 MHz system actually provides greater availability than the 200 MHz system, due to the nonlinear effects of terrain on radio wave propagation. We find that the ability to route traffic alone may not be sufficient to overcome the inherent range limitations of higher frequencies.

The Effect of Greater Transmission Power

We next consider the effect of greater radio transmission power to overcome the range limitations of higher frequencies. We use our theoretical radio models to compare a theoretical A_{PTP} radio operating at 65 MHz with 10 watts of transmission power, to A_{Total} routable systems operating at 400 MHz with transmission powers ranging from 10 to 100 watts. Figure 7 presents average battalion network availability for all three scenarios.

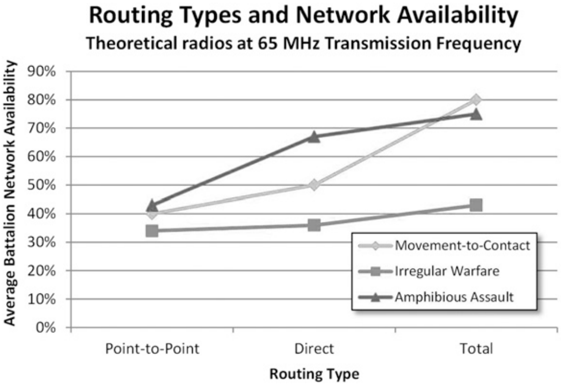

Figure 5. Average battalion network availability for three routing types. All other things being equal, increased connectivity provided by the ability to route traffic results in greater network availability.

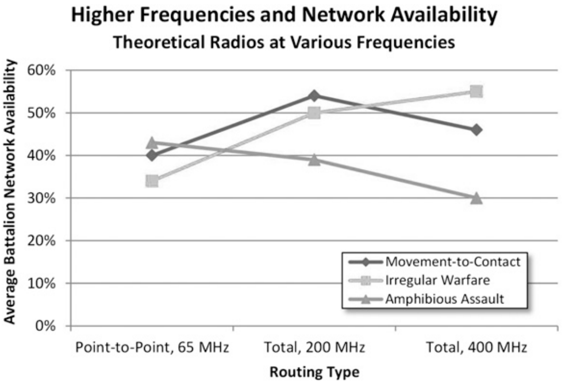

Figure 6. Average battalion network availability with varying operating frequencies.

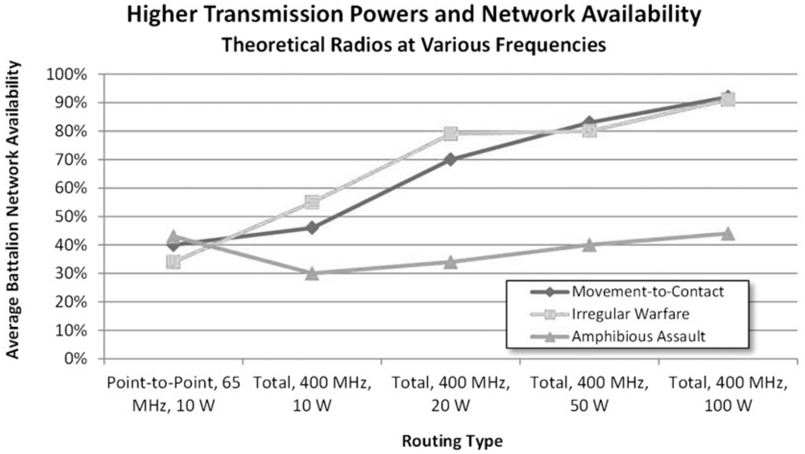

Figure 7. Average battalion network availability with varying transmission powers.

For all three scenarios, greater transmission power provides greater availability for routable networks, results similar to Alderson et al. (2011b). Note that in the amphibious assault scenario, a substantial amount of transmission power (100 watts) is required for a routable network at 400 MHz to provide the same level of availability as a PTP network operating at 65 MHz with a mere 10 watts of transmission power. Per Equation (1), received signal strength (and thus network availability) can be increased by increasing antenna gain or transmission power, or by decreasing loss. Greater transmission power and/or more sensitive receivers and antennae may be necessary for MANET radios to provide the same network availability as non-MANET radios at lower frequencies.

The Effect of Intermediate Nodes

The remainder of our analysis considers only actual, real-world radios. We next consider the effect of the presence of intermediate nodes on MANET performance, comparing the PTP base case against the VHF and UHF MANET cases. See MCCDC (2011) for a detailed list of specifications. Figure 8 presents the battalion network results for the movement-to-contact (MTC) scenario, results representative of all scenarios and network tiers. Note this scenario

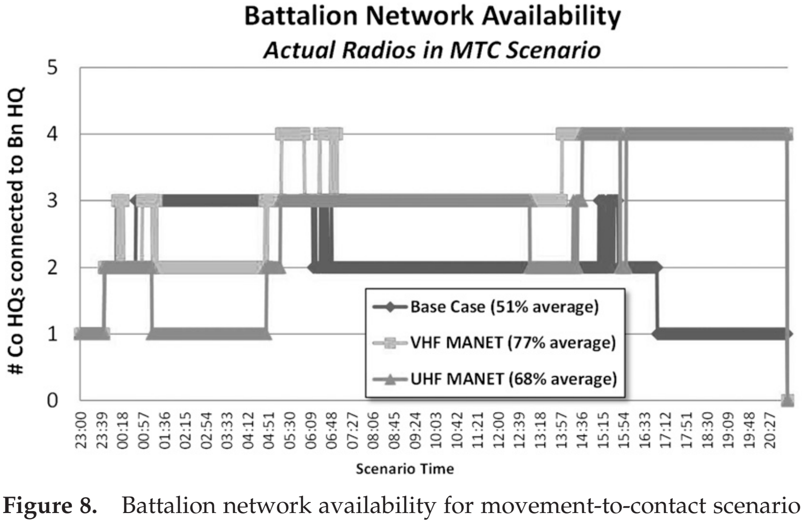

Figure 8. Battalion network availability for movement-to-contact scenario.

includes an FSCC, so there can be a maximum of four nodes connected to the battalion node.

We see that over the entire scenario, the MANET cases deliver higher average battalion network availability than the PTP base case, but there is a substantial period of time (01:44-04:48) in which neither MANET case can provide the same network availability as the base case. Similar outages occur in all three scenarios and at different tiers within the battalion. These outages occur when intermediate nodes are unable to relay traffic from source to destination. In this scenario, the company nodes (mounted in armored vehicles) transit behind terrain that blocks RF transmission, and no other nodes are able to relay the required company traffic to the battalion commander node. MANETs can provide increased network availability only when intermediate nodes are in range, yet the location of nodes is often driven by operational (rather than communications) requirements. Without these nodes, a MANET is essentially reduced to a PTP network, and as MANETs operate at higher frequencies (subject to greater signal attenuation), a MANET forced into PTP mode will provide less network availability than a traditional, lower-frequency PTP network.

The Effect of Dedicated Airborne Relay Nodes

We next consider the benefit of a dedicated airborne relay node, such as an unmanned aircraft system (UAS). Dedicated airborne relay nodes are often used to increase network performance (Krout et al., 2003) because radio waves transmitted from airborne nodes are subject to much less signal attenuation from terrain features than terrestrial nodes, and thus can generally connect at much greater distances. We compare our PTP base case against both MANET cases and a case with an added UAS node (modeled as a company-level node) to serve as a dedicated airborne relay node for battalion traffic. This device serves as neither a source nor destination for any communications traffic, but solely as a relay. Figure 9 presents the average battalion network availability results for all three scenarios. The left side presents the base case and the VHF MANET case, and the right side presents the base case and the UHF MANET case.

In all three scenarios, the addition of a UAS to a MANET provides network availability at least equal to that provided by the original MANET. In all but one scenario (amphibious assault with UHF MANET radios), the UAS increases network availability. Note that in the irregular warfare scenario, both the VHF and UHF MANETs are unable to provide network availability equal to the base case without the addition of the UAS, due to the impact of terrain on higher frequencies. In the amphibious assault scenario, even the addition of a UAS is unable to overcome the inherent range limitations of UHF MANET. We find that although dedicated airborne relay nodes are not a panacea for availability shortfalls, they can greatly increase network availability, and may be required

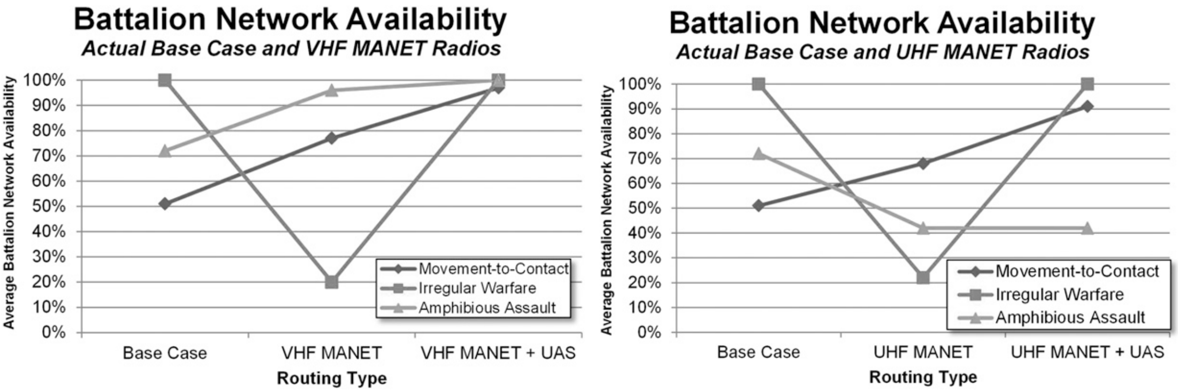

Figure 9. The effect of the addition of a dedicated airborne relay on battalion network availability for each scenario.

in certain circumstances for MANETs to provide the same level of network availability as a lower-frequency PTP network.

The Effect of Additional Loss

Thus far, we have examined network availability with the assumption that signal loss (other than that due to terrain obstructions) is constant. Per Equation (1), additional signal loss will reduce the SNR and may reduce network availability. We now explore the effect of additional loss on network availability. This additional loss could represent active jamming, background noise, vegetation, inclement weather, bad connectors, and so on. We incrementally add up to 30 dB of additional loss to each point-to-point arc $(i, j) \in A$, and we assume this loss is constant across the entire spectrum. We conduct this analysis across all scenarios and cases. Figure 10 displays the results for the movement-to-contact scenario, representative of the other two scenarios.

In this chart, the horizontal axis indicates the additional signal loss introduced to all arcs, from 0–30 dB, and the vertical axis indicates average battalion network availability as a percentage. These results indicate that in high-loss environments, the base case may provide greater network availability than the MANET cases. The following simple example explains these results.

Consider two nodes that must communicate. In a point-to-point network, these two nodes must communicate directly. In a MANET, the nodes are able to use intermediate nodes to relay traffic. A point-to-point arc has surplus received signal strength if the received signal strength is greater than the required threshold. This is analogous to having extra range.

In the scenarios and cases considered in this study, the base case arcs (i.e., VHF point-to-point arcs) typically have greater surplus received signal strength than the MANET arcs due primarily to the lower transmission frequency of the former. Hence, in environments with greater loss, those point-to-point arcs in MANETs (with less or no surplus signal strength) will disconnect first. A MANET is capable of rerouting traffic along alternate paths, if they exist. However, our conceptual radio model calculates the optimal path between any two nodes, so any other path will have connections with even less surplus received signal strength and/or more hops than the selected optimum.

In the realistic scenarios considered in this study (and by Hong et al., 1999), nodes tend to remain relatively close to other nodes in their immediate chain-of-command (e.g., squad nodes within a particular platoon remain near each other). This ‘‘clumping’’ prevents the routing of traffic because possible intermediate nodes are insufficiently dispersed. Should the intermediate nodes be more evenly dispersed, traffic can

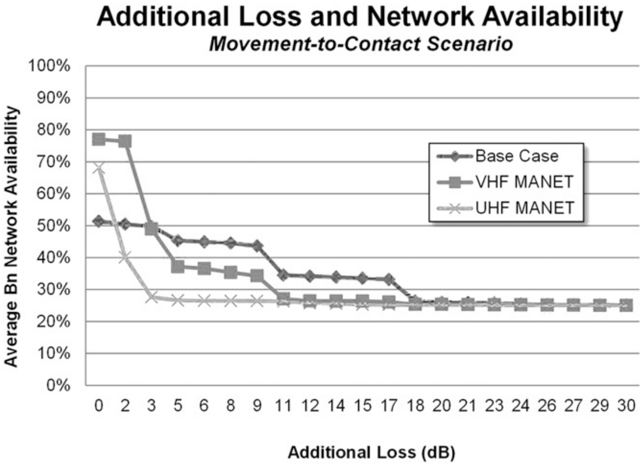

Figure 10. The effect of additional signal loss on battalion network availability in the movement-to-contact scenario.

be routed between the required nodes. These results suggest that rather than MANET enabling dispersion, dispersion may enable MANET. In other words, in a high-loss environment, MANETs may not fully function without sufficient dispersion.

This finding has a powerful implication. Traditionally, communications networks support military operations, not the other way around. Certainly, the ability to communicate has always been limited by technical constraints, and MANET technology is not a panacea to this problem. MANET offers the military commander exciting new capabilities, but if he or she wishes to utilize the full capabilities of MANET, including extending MANET connectivity down to the lowest levels, then tactics may need to be adjusted to support this requirement.

The Effect of Channel Bandwidth on Network Throughput

According to Equation (2), higher frequency systems (generally subject to greater signal attenuation) require greater bandwidth to provide throughput equal to systems operating at lower frequencies. Our final analysis considers the allocation of bandwidth to enable MANET systems to provide sufficient throughput rates. To calculate total network throughput, we solve our version of the SRRA problem using GAMS (2011) at each time step within our scenarios, and sum the throughput values between each source-destination pair $(u, v) \in D$ at each tier in the battalion.

First, we examine our three cases using theoretical radios operating at the same bandwidth (500 KHz). The results for the battalion network in the MTC scenario are presented in Figure 11. The vertical axis indicates the total network throughput between each company node and the battalion node. Even without the ability to route traffic (i.e., a PTP network), the 65 MHz PTP system is able to provide substantially more network throughput than the 225 MHz or 1.125 GHz MANET system. This is in keeping with our earlier analysis showing the propagation limitations of higher

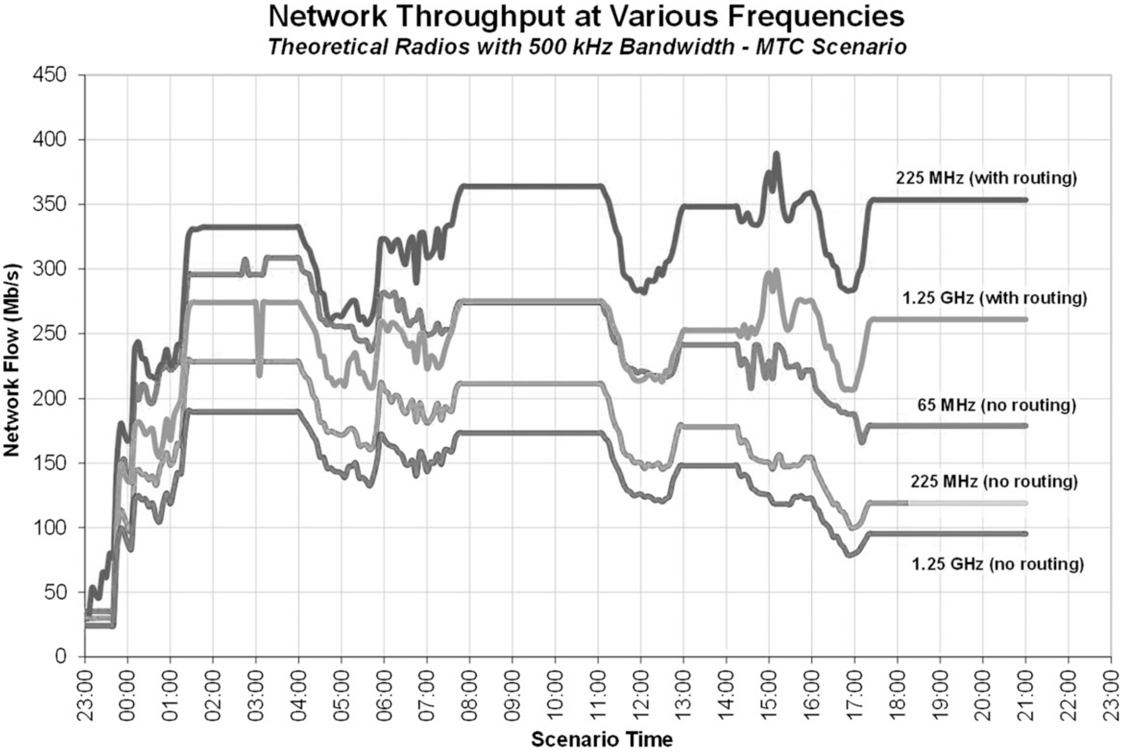

Figure 11. Network throughput for theoretical radios using a 500 kHz channel. By adding the ability to route, higher-frequency systems can outperform lower-frequency systems without the ability to route.

frequencies. By simply adding the ability to route (i.e., a MANET), the higher-frequency systems are able to outperform the 65 MHz PTP system. We find that the ability to route traffic alone can increase network throughput; larger channel bandwidths may not be necessary.

Finally, we measure network throughput while varying both operating frequency and bandwidth for a MANET system in the MTC scenario. The results for the battalion network are presented in Figure 12. In this chart, the area of each point is proportional to the sum of the average throughputs between the company and battalion nodes. Such a plot serves as a visual aid in understanding the effects of frequency and bandwidth on network throughput. Here, doubling the bandwidth doubles network throughput, as predicted by Equation (2). However, halving the operating frequency results in only a marginal increase in network throughput, due to the specific (nonlinear) effects of terrain on RF propagation. Such information can inform RF resource allocation decisions.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

The Marine Corps is actively pursuing the use of MANET technology to extend digital communications throughout the battlefield. Yet, MANET technologies are not a panacea to tactical communications difficulties, nor does their use alone enable greater dispersion of forces. The requirement for sufficient intermediate nodes implies that greater fielding of MANET radios to all echelons may increase network availability throughout the infantry battalion. As radio technology continues to approach limitations imposed by physics, and USMC forces increasingly operate in electromagnetically noisy urban environments, dedicated airborne relay nodes—immune to the significant propagation losses suffered by terrestrial radios—will become increasingly important. The sensitivity of MANETs to high-loss environments implies that if the USMC is to push data connectivity down to the lowest

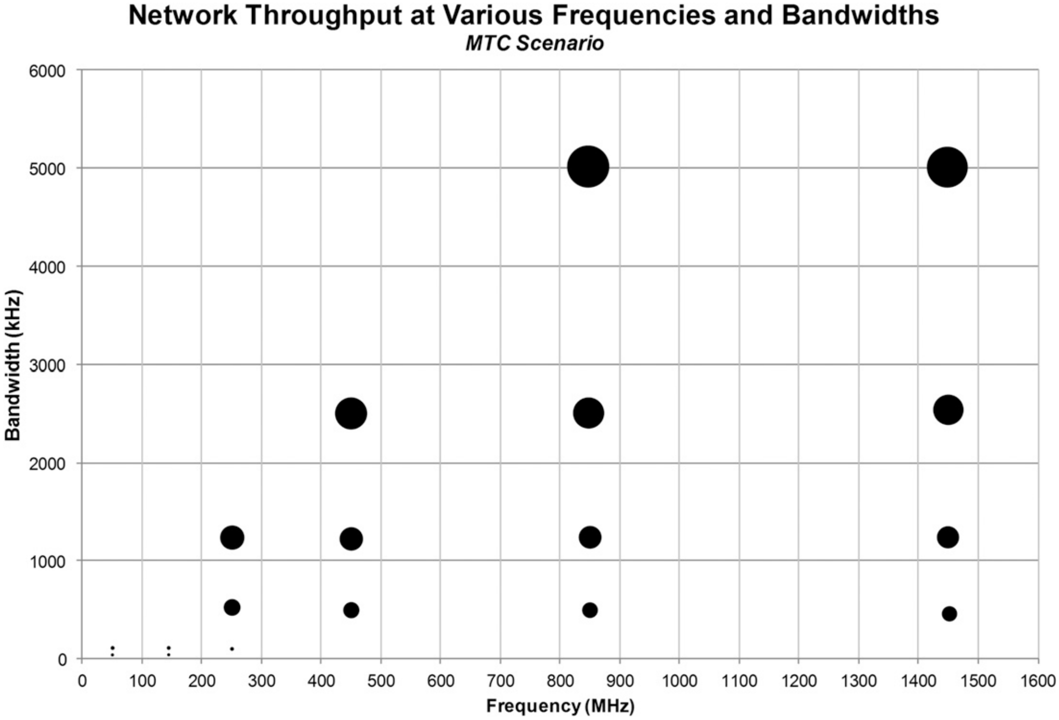

Figure 12. Network throughput for theoretical MANET radios, varying both bandwidth and frequency. The area of each point is proportional to the network throughput, ranging from 8.47 Mbps to 3.88 Gbps.

levels within the battalion, tactics may need to be modified to support the full use of MANETs. The ability to route traffic alone can increase network throughput, making MANETs particularly useful in bandwidth-constrained environments.

Possible future work could include an examination of specific network disruptions (accidental or intentional) on the design and operation of MANETs (e.g., Grotschel et al., 1995; Shankar, 2008; Alderson et al., 2011a), or the effect of slight perturbations of node locations. This research assumes sufficient EM spectrum exists; ongoing research at MCCDC considers the efficient allocation of spectrum among several MANET systems. Additionally, our first principles-based analysis technique could complement bench-top and field testing, to support model-test-model research.

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ABBREVIATIONS AND ACRONYMS

AA: amphibious assault scenario
AGI: Analytical Graphics Incorporated
AP: access point
bps: bits per second
C2: command and control
COTM: communications-on-the-move
DO: distributed operations
DR: disaster relief
EPLRS: Enhanced Position Location Reporting System
GHz: gigahertz
GUI: graphical user interface
HA: humanitarian assistance
ISR: intelligence, surveillance, and reconnaissance
IW: irregular warfare scenario
kHz: kilo Hertz
ITM: Irregular Terrain Model
kbps: kilobits per second (1,000 bits per second)
LOS: line of site
MANET: mobile ad hoc network
Mbps: megabits per second (1,000,000 bits per second)
MCCDC: Marine Corps Combat Development Command
MCTSSA: Marine Corps Tactical Systems Support Activity
MHz: mega Hertz
MTC: movement-to-contact scenario
PTP: point-to-point
RSS: received signal strength
SME: subject matter expert
SNR: signal-to-noise ratio
SRRA: Simultaneous Routing and Resource Allocation
STK: Satellite Toolkit
TIREM: Terrain Integrated Rough Earth Model
UHF: ultra high frequency
USMC: United States Marine Corps
VHF: very high frequency
WMN: wireless mesh network

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