Framework for Measuring the Impact of C4ISR Technologies and Concepts on Warfighter Effectiveness Using High Resolution Simulation

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Abstract

A C4ISR architecture for future forces is a major concern to the Army. This report describes progress of an on-going project to develop a framework for assessing individual communication technologies and concepts by accounting for technological and operational detail. Assessments of communication performance (e.g., message delay and message completion rate) factor terrain, mobility, and other scenario specific details via high-resolution simulations. For such measurements, excessive run-times can be a problem. This is usually the case for high-resolution simulation of communication networks. However, in this paper, it is shown that high-resolution communication network simulation runs (using Qualnet©), although time consuming, can be used to capture the dynamics of communication performance in closed form expressions or meta-models. The meta-models can then be embedded into force-on-force simulation (JANUS) to get perhaps the most important performance measure, e.g., warfighter effectiveness. This forms a framework that supports detailed, scenario specific examination of the impact of C4ISR on warfighter effectiveness.

1. Introduction

A C4ISR architecture for future forces is a major concern to the Army. This report describes progress of an on-going project to develop a framework for assessing individual communication technologies and concepts by accounting for technological and operational detail. Specifically, this paper reports on efforts to provide assessments by accounting for terrain, mobility, and other scenario specific details via high-resolution simulations and other methods.

There are various types and levels of measures of C4ISR performance. At a detailed level, communication performance measures like message delay and message completion rate, which are a function of terrain and many other technical details, can be assessed with simulation tools. For such measures, excessive run-times can be a problem. In general, high-resolution simulation of communication networks is usually expensive in this regard. In this paper, it is shown that high-resolution communication network simulation runs, although time consuming, can be used to capture the dynamics of communication performance in closed form expressions or meta-models. The meta-models are then embedded into force-on-force simulation (JANUS) to get perhaps the most important performance measure, e.g., warfighter effectiveness. This forms a framework that supports detailed, scenario specific examination of the impact of C4ISR on warfighter effectiveness.

This paper describes a framework for studying communication networking capabilities. An existing high fidelity communication network simulation tool called Qualnet© is used. Simulation experiments are described along with corresponding statistical analyses of the results. The communication network meta-models[1] developed are intended for use as part of a larger effort to embed representations of dynamic performance of communication network into force-on-force simulations. A number of parameters are factored including antenna technologies, frequency utilization, UAV and SATCOM concepts and usage, and information distribution options. These are all technology concepts and options that affect communication and connectivity and hence warfighter effectiveness. In general, this report considers how communication models can be utilized so that the impacts of various C4ISR technology options, as well as other situational factors, are reflected in combat simulations.

This report is organized as follows. In the first section, a description is given of the methods and tools used to measure network performance and factors of interest that might affect it. In section 2, details on the meta-modeling approach utilized are presented and a list of the factors of interest to this study is provided. This is followed by a section on some general network simulation runs that helped to identify the trade-offs associated with communication and information dissemination options for C4ISR architectures. Section 4 describes the major research effort of this report, which is the result of a meta-modeling effort to capture the dynamic communication performance. This is done by focusing the modeling effort on four distinct terrain boxes. Observations, conclusions, and a discussion of on-going and future work are also included. Appendix A provides more details on synthesized models.

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[1] The concept of meta-modeling is related to response surface modeling.

2. Methods and Tools

One goal of the project documented in this report is to translate various communication technology options into impacts on network performance. The main approach towards achieving this goal is summarized as follows: Various technologies and factors that impact network performance are chosen and set at levels of interest. Qualnet simulations are run. Network performance during these simulations is recorded. The outcomes of these simulation experiments are used to construct the performance models to be used in combat simulations. This is further described as five steps:

1. Determine the important factors that impact network performance.
2. Use an existing commercial high fidelity communication network simulator to gather data on performance responses.
3. Develop performance models (meta-models) from the data.
4. Incorporate functions into combat simulator to assess impact on warfighter.
5. Evaluate functions to assess technology options in terms of other measures.

The steps above form an analysis framework that is proposed and being tested. It is developed so that it can incorporate JANUS (or perhaps JCATS or others) force-on-force simulations (Step 4). JANUS is a high-resolution force on force simulation program that models individual entities in combat situations. The output of these simulations is used in analysis of performance under specific conditions and situations; two important features that JANUS takes into account in simulations are attrition and terrain. The screen capture in the figure below shows the high-resolution nature of

JANUS, i.e., individual entities are represented for opposing forces and terrain is factored.

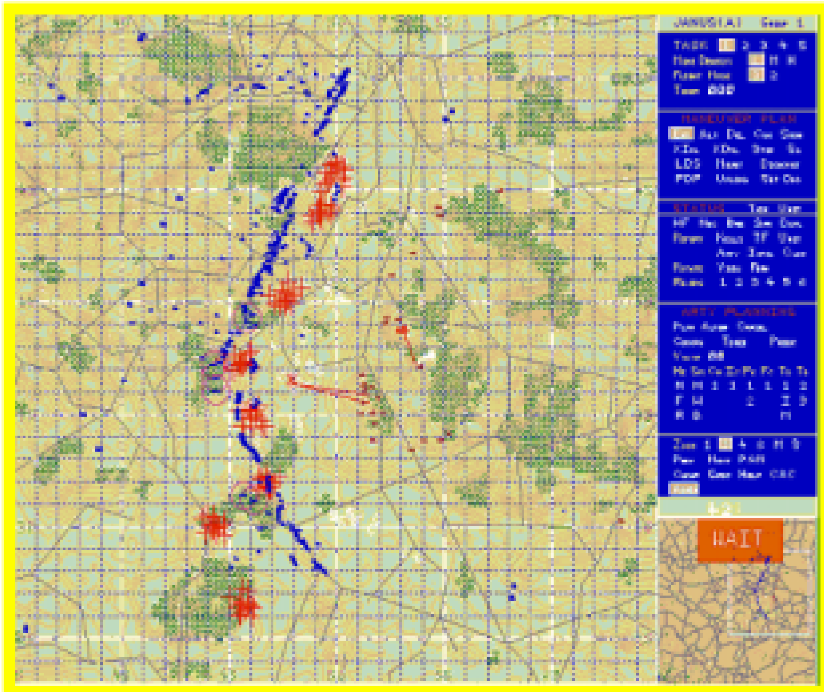

Figure 1: JANUS Screen Capture

Qualnet is a communication network modeling tool used to run the experiments documented in this report. It has origins with the DARPA GloMo[2] project. Qualnet developers claim it to be an accurate and efficient communication software used commercially and by some within DoD to test the bounds of current communication systems as well as to experiment with new communication system ideas. Simulation run-times vary based on the network size, traffic, and other factors. For the experiments reported in this chapter, simulation-time to real-time ratios were consistently less than 5:1 (real-time to simulation-time). Like Janus (and JCATS), Qualnet takes into account terrain using map data (e.g., DTED1).

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[2]see B. Leiner, R. Ruth, S. Ambatipudi, "Goals and Challenges of the DARPA GloMo Program," *IEEE Personal Communications*, Dec. 1996.

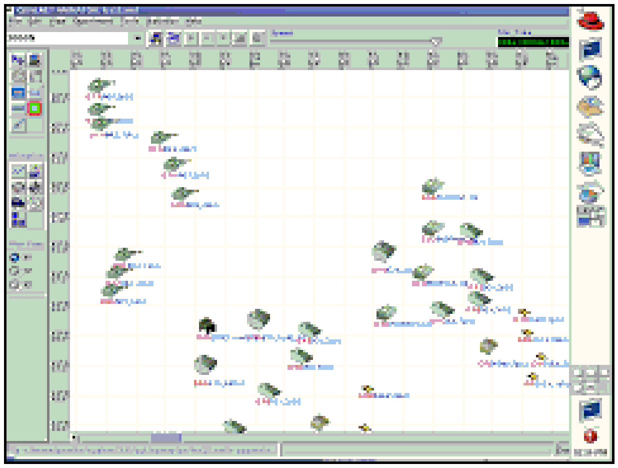

Figure 2: Qualnet screen capture

The framework proposed in this section is one that will utilize both these two high-resolution simulation tools in order to provide analysis of combat effectiveness that dynamically factors communication performance. This merging could be accomplished by directly inserting Qualnet into JANUS, but run-time is an important issue for high-resolution simulations. Instead, meta-models are developed to capture the effects of the technology and other factors of interest, and can realistically represent network performance in combat without adding the overhead time of directly using a communication simulator.

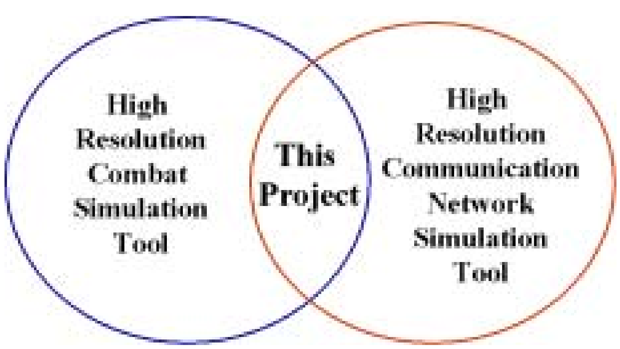

Figure 3: High-resolution Modeling is Incorporated

Why A Meta-modeling approach?

A communication network simulator is a mechanism that turns factors (e.g., frequency, number of UAVs, radio power, node density, frequentness of data transmissions, etc.) into performance responses (e.g. packet delivery ratio, end-to-end delay). In this sense, the network simulator is a function. A large number of simulation runs can be used to provide enough information so that an algebraic expression of the performance response is formulated as a function of the factors of interest via regression analysis. This is called meta-modeling (Law and Kelton, 1992).

Communication network simulation is complex and time consuming. A communication network simulator could be integrated directly into a force-on-force simulator so that operational performance and communication performance are both determined with a high degree of resolution. But, there is an added cost in terms of computational time and complexity of such a pairing. Meta-modeling is an alternative. A meta-model can capture the effects of the technology and other components of interest and can realistically represent network performance. This research effort proposes that it can be incorporated into combat simulations so that communication (and information dissemination) performance can be dynamically represented.

Factors of Impact Addressed

There are a large number of relevant factors that impact communications performance and C4ISR performance in general. A small subset of key factors was selected to test the proposed framework and modeling approach. They are as follows.

1. Terrain (elevation variation, foliage, etc.)
2. User (radio) throughput capability (in Kbps)
3. Signal frequency

4. Message data rate
5. Presence of UAV's to serve as reconnects
6. Density of nodes on the same network
7. Distance between nodes
8. Line-of-sight between nodes

Terrain Considered

Figure 4: Terrain Boxes (areas)

The roughness (or varying elevation[3]) impacts line-of-sight, signal attenuation, and other factors that can severely enhance or degrade communication capability. Four terrain boxes were used in this experimentation process. They are shown in the figure. Area 4 is shown as the lower right box. It has a 40km x 40km land area that is not

[3] See Brennan (1987) for a discussion of use of terrain elevation data in metamodels of communication performance.

contiguous with the other boxes and is ~60 km away from the box labeled Area 2 in the figure.

The approach is to model network performance inside each of the individual boxes via simulation. The boxes vary in size and terrain roughness as shown below in the figures that follow.

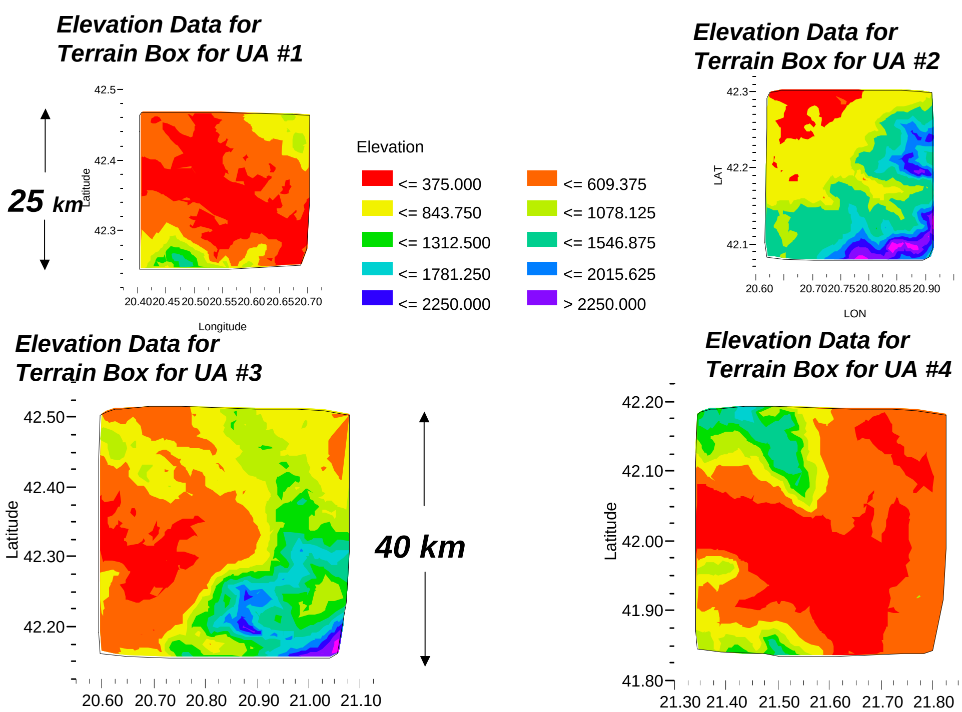

Figure 5: Elevation Details of Terrain Boxes

Signal Frequency

Lower transmission frequencies (e.g., 200-400 Mhz) propagate across rough terrain and through foliage better than higher frequencies (e.g., 2-38 GHz). However, there is more availability at higher frequencies in terms of spectral allocation. Furthermore, higher frequencies are less detectable. Candidate bands being considered for JTRS (Boeing, 2002) include the following:

1) 225-400 MHz

2) 1350-1390 MHz
3) 1755-1850 MHz
4) 2200-2290 MHz
5) 2400-2500 MHz

User Transmission Rate

The rate that a radio transmits data varies. An existing radio like the NTDR has a reported user data rate of 288 Kbps (maximum). According to the JTRS Wideband Network (WNW) Functional Description Document (JTRS Joint Program Office, 2001), "the JTRS WNW shall support user throughputs greater than 2 Mbps as a Threshold and 5 Mbps as an Objective". In our experimentation, we consider 2 Mbps and 6 Mbps user data rates for the radios modeled.

Message Data Rate

Data rates vary by message type. Voice data can be as low as 8Kbps. Video teleconference can be 256 Kbps or higher. Streams of live video can be at 1 Mbps and higher. The size of a COP and the frequentness of its dissemination could span all of the aforementioned rates. Thus, simulation tests will also have to span these data rates.

Presence of UAVs as Reconnects

Vertical nodes that support communication relay can be in the form of fixed wing aircraft, unmanned aerial vehicles of various sizes and operating altitudes, and high altitude airships (> 60,000 ft). For the terrain boxes identified in this chapter, we consider 0, 4, and 8 UAVs as dedicated relay platforms. One objective of this research effort is to determine the required number of relay platforms needed to provide the required reliable, accurate communications connectivity that enhances warfighter.

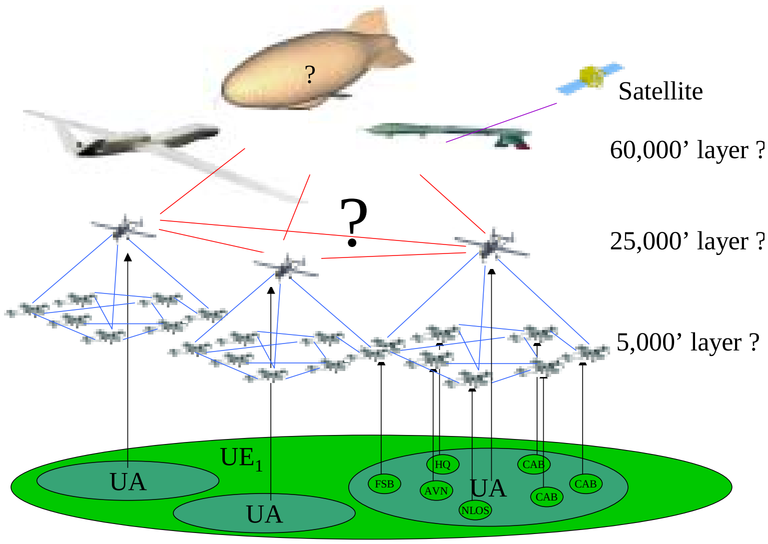

Figure 6: Concept for a Multi-layer Communication Architecture- Signal Center (Kioutas, 2003)

Density of Nodes on the Same Network

The terrain boxes considered cover areas of 25km x 25km in two cases and 40 km x 40km in the two others. Nodes are dispersed so that there is experimentation with 36 nodes, 72 nodes, and 145 nodes. This means that densities from 0.0225 nodes/km^2 to .232 nodes/km^2 are considered. A model with density as a factor facilitates a model response that is dynamic, i.e., changes with attrition. This is a key attribute of our approach and highly appropriate given its intended use as part of a force-on-force combat simulation exercise.

Distance Between Nodes

The nodes in the terrain boxes are randomly dispersed such that the range between individual nodes range from very close (< 0.5 km) to distant (35 km).

Line of Sight

The line of sight between two nodes represents the condition of whether or not there is any obstruction between the path of a sender and a receiver of a message. It is impacted by the relative elevation of the node-pairs and of course the surrounding terrain.

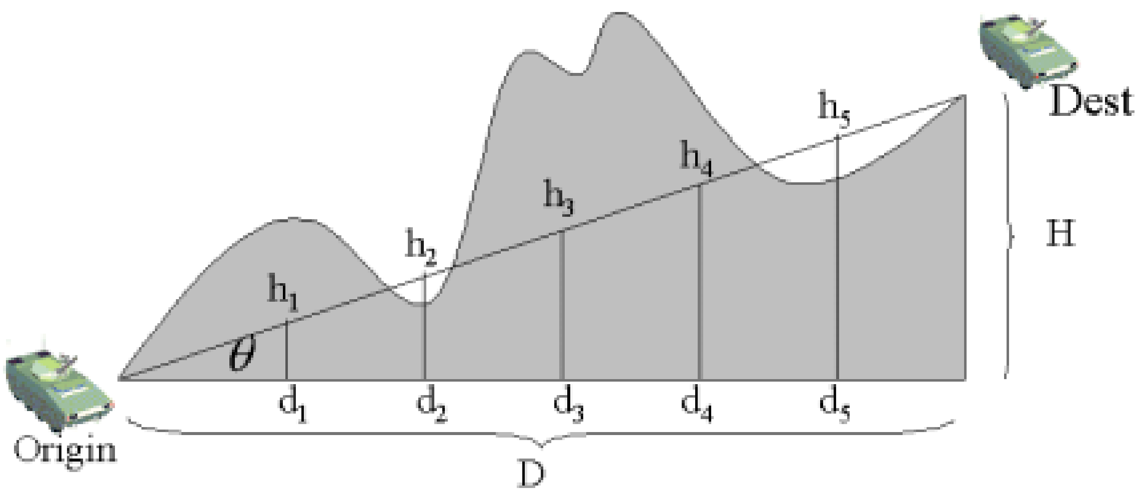

Figure 7: Assessing line-of-sight (LOS)

In the figure, the height of the destination relative to the origin is shown. Intermediate points (d1, d2, d3, etc.) along the path between origin and destination, and the corresponding heights, determines whether a pair enjoys line-of-sight. The example in the figure depicts a non-line-of-sight condition.

Line-of-sight, based on relative elevation data, between a single node-pair, may not be suitable alone as an indicator of communication performance.[4] This is because a network may facilitate a simple path that involves one or more hops through intermediate nodes. Perhaps a more useful factor measures the average line-of-sight a given node has with all of its neighbors. The figure below provides an example calculation of such a measure (In the figure, a blocked line of sight equates to 1 and a completely clear line of sight is zero.)

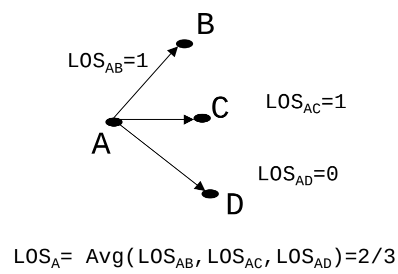

Figure 8: Simple Measure of Average Line-of-Sight

Later in this report, a description is given of measurements that were taken of the average line-of-sight a node has with all of its neighbors. This factor appeared to improve the fit enough to suggest that it is a useful measure. More testing and examination is needed.

3. General Experiments

Simple Simulation Experiments to Address Scalability

A number of simulation experiments were performed to generally assess communication network capabilities. We described three sets of simulation experiments. In the first, Qualnet is used in a terrain-less set-up. Nodes are distributed at various spacing. The network is fully-connected, i.e., each node is connected to another as shown below.

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[4] A 1987 CECOM report (Brennan, 1987) reached a similar conclusion.

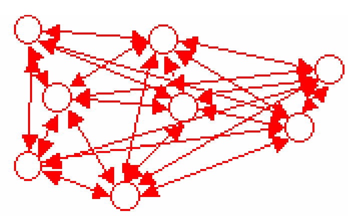

Figure 9: Depiction of a (Nearly) Fully-connected Network

The results from these tests are shown below. They highlight one of the most critical aspects of a C4ISR (or battle command) network – scalability. In the figure below, a data rate is offered (transmitted) by each node. For the small, three-node network shown as the top line, the load can be handled, i.e., what goes in is what goes out. For larger networks like the bottom curve, which represents a 49-node network, throughput above even a low rate (e.g., 24Kbps), is limited.

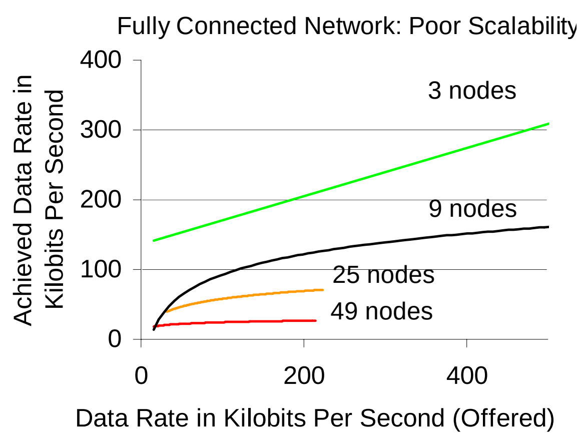

Figure 10: Assessing Scalability

This is a known result in networking (See Gupta and Kumar, 1999). It suggests that fully connected networks like the one shown in the figure will only exist in small numbers and/or with minimal data traffic. Hierarchical or regionalized information dissemination will almost certainly be required. This is depicted in the figure below.

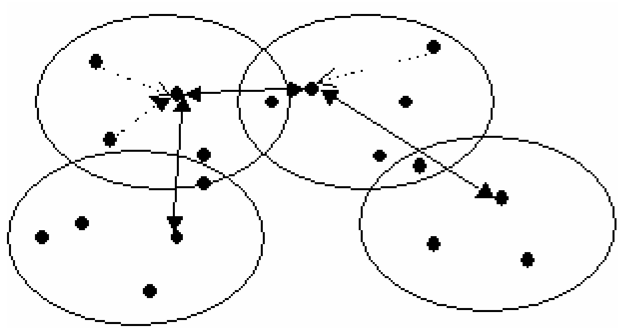

Figure 11: Regionalized/Hierarchical Network

The point made by the results of these simple experiments is to demonstrate the inherent scalability issue associated with wireless communication in general. Aggregation or clustering, in terms of the communication architecture, has always been one approach to addressing this concern. A fully decentralized, fully-connected architecture in which each node communicates with every other node is only practical for small networks and/or networks that can exist with very low data rates (e.g., 24Kbps). A regionalized approach to information dissemination (and/or data fusion) is more practical (and probably a necessity) for larger networks.

A second set of simulation experiments was exercised. This time, using terrain and force structure that reflects a (future) company sized Army unit. The unit was simulated with varying message traffic. Specifically, the time a UAV sensor is used, as a percentage of the time the sensor is transmitting data, was varied as well as the frequentness of the COP update message. A specific terrain map was used. It is shown below.

Figure 12: Terrain Map Used

A small company sized force was emplaced in this specific region as shown in the figure below.

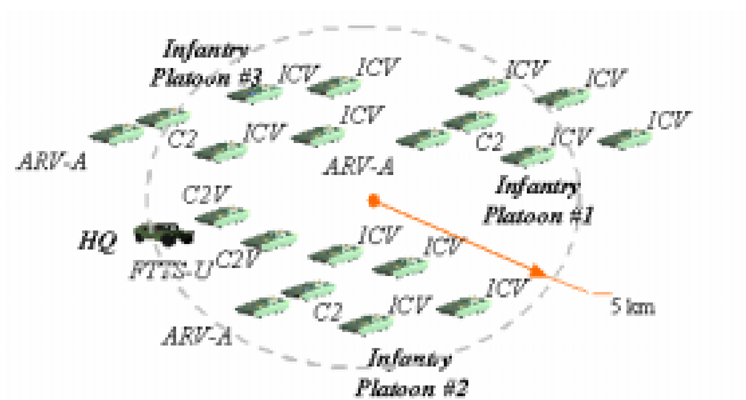

Figure 13: Generic Force Laydown

The simulation experiments consisted of the following steps:

1. Vary UAV Sensor data usage
    a. 0% Tx Active
    b. 25% Tx Active
    c. 75% Tx Active

d. 100% Tx Active

2. Vary COP Update Freq.

   a. Very Frequent (10 times / min)

   b. Infrequent (once every 2 minutes)

3. Assess Delay & Completion Rate

   a. For COP Message

   b. For UAV Sensor data

The data distribution included COP messages going out and SA message coming in as shown in the figure below.

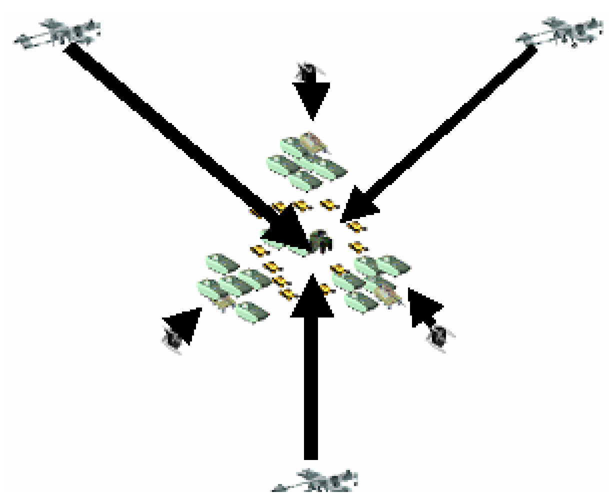

Figure 14: UAV Sensors Transmitted Imagery Back to a Command Vehicle

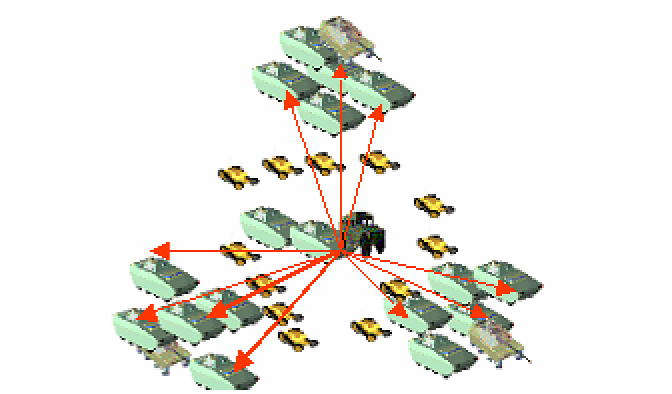

Figure 15: A Command Vehicle Transmitted a COP Update Out

Raw data from the simulation runs is shown in the figure below. The figure suggests that when sensor usage is below 50% of the time and COP updates are held to no more than once a minute, then this allowed completion rates to be above 75%. There appears to be a trade-off with the degree of sensor usage.

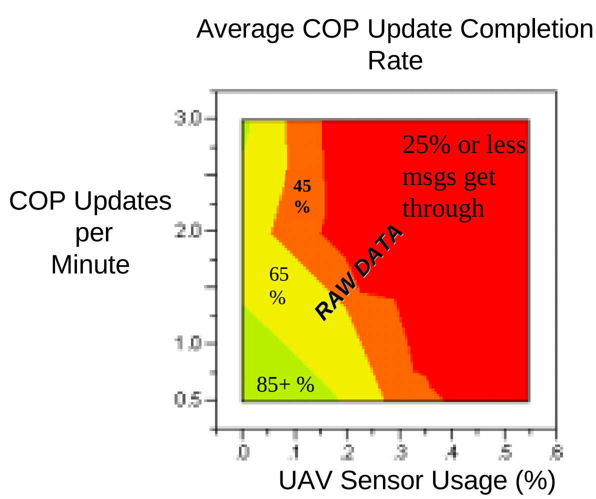

Figure 16: Simulation Results

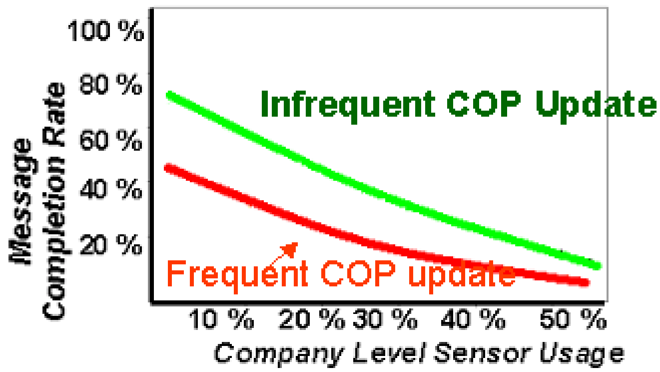

Figure 17: Tradeoffs

The figure suggests that sensor usage below 50% of the time and COP updates held to no more than once a minute was sufficient in allowing completion rates to be above 75%. There appears to be a trade-off with the degree of sensor usage.

These results and observations were somewhat intuitive. The need to transmit sensor data and conflicted with the need to transmit cop update data, when sharing a communication channel. The following observations cited are drawn from simulation results: (1) Less frequent COP updates and limited sensor usage are needed to get adequate network performance; neither will be able to unconstrained (2) aggregated architectures for information dissemination and data fusion will be required to handle the scalability issues. One resolution to the 1st observation is to put sensor links and COP update (SA) links on separate, non-contending channels (assuming spectrum availability is not an issue). Putting sensor data on separate data links (channels) seems necessary.

4. Experiments To Synthesize Meta-models

A factorial design (Law and Kelton, 2000) was employed for the factors described earlier (transmission frequency, number of UAVs, etc.) and shown in the figure below.

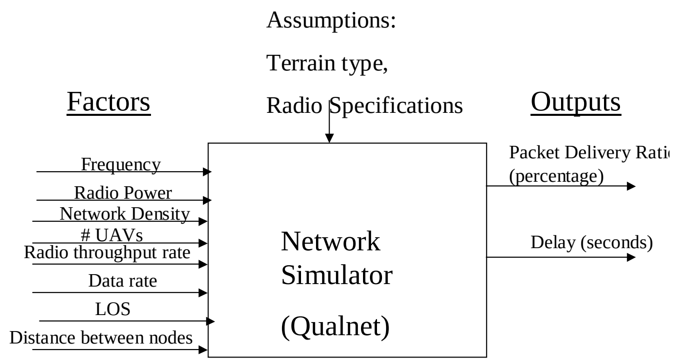

Figure 17: Factors and Responses

The number of nodes was set such that these experiments could represent a Battalion sized force at various levels of attrition. An example is shown in the table below. The table shown is not the actual experiment designed but is shown to indicate how the factors were varied; the last two columns represent the responses sought, which are PDR (packet delivery ratio) and end-to-end delay. Thousands of simulations were run for each area of interest.

Table 1: Example Design of Experiments

#	frequency	# UAVs	density	Radio Power	Radio Throughput	Data Rate	PDR	Delay
1	2 GHz	0	145	2 W	2Mbps	16Kbps	result	result
2	1 GHz	4	72	20 W	2Mbps	32Kbps	result	result
3	0.4 GHz	8	36	1600 W	2Mbps	64Kbps	result	result
4	0.2 GHz	0	145	2 W	6 Mbps	160Kbps	result	result
5	2.5 GHz	4	72	20 W	6 Mbps	320Kbps	result	result
6	0.1 GHz	8	36	1600 W	6 Mbps	533Kbps	result	result

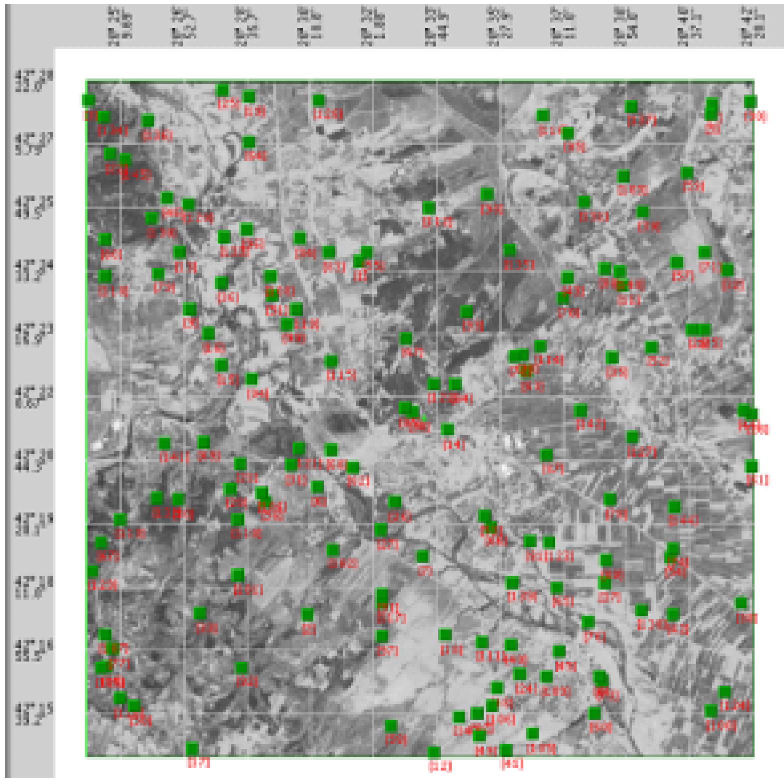

Figure 18: Node Placement on Terrain Box 1

Experiments were conducted with a small Bn-sized unit. Approximately 145 nodes randomly scattered across a 25km by 25km area in the Macedonia-Serbia area as shown in the figure above that is referred to as terrain box 1. The COP update (in terms of size and frequency) was varied. Network performance was observed as function of frequency, mobility, UAV usage, etc. The terrain is fairly flat.

All of the experiments were 20-minute Qualnet simulations. These experiments focused on COP update messages. The COP update is dissemination of information by one informed node (e.g., the commander control vehicle) to everyone else giving them information about the whereabouts of all other relevant vehicles (as well as other information including perhaps enemy forces and weather and terrain data). The dissemination “Architecture” is as shown in the figure below. The size of a COP update is varied as it can be made small or large and sent frequently or infrequently.

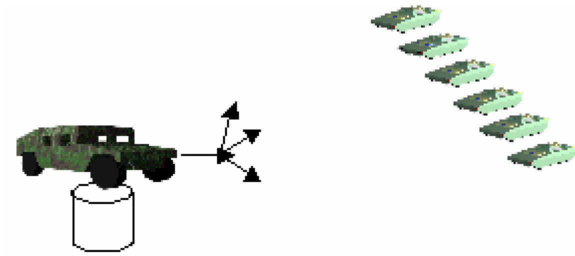

Figure 19: Information Dissemination

There are no other messages being transmitted on the network for these experiments. This is equivalent to the COP update messages receiving its own dedicated channel on the system. For each experiment, the variables of interest were set and recorded and then the simulation was run; network performance measures were then recorded.

Performance Measures (Responses)

The performance measures being tracked are packet delivery ratio[5] (PDR) and delay[6]. PDR is defined as the number of packets received by a node divided by the number of packets sent to it; the packet delay is defined by the time, in seconds, the packet was received minus the time that the packet was sent. One or more (*n*) packets make up a message. So, the likelihood that a message gets through is related to the likelihood that *n* packets get through.

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5 PDR = # of packets received / # of packets sent

6 Delay = time packet received – time packet sent

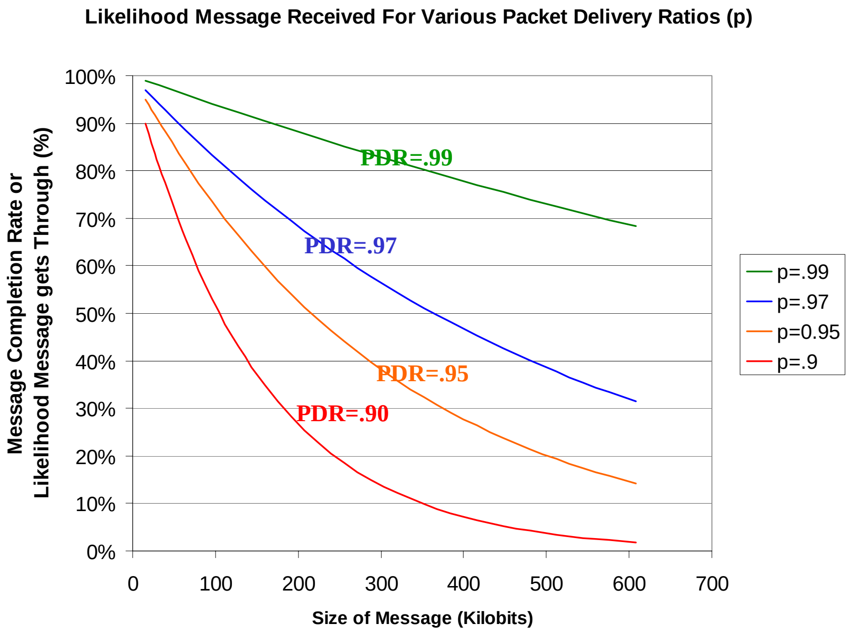

Figure 20: Packet Delivery Ratio and MCR

Clearly, multi-packet messages require high packet delivery ratios in order to ensure a high message completion rate. The chart in the figure assumes that message completion rate has the probability distribution of the negative binomial distribution.[7]

Factors

The factors of interest were chosen previous to running the experiments as well as the possible levels at which they will impact the network. These factors are varied systematically throughout all of the experiments as alluded to in the table. The specific ranges for the frequency of the transmissions were varied across 6 levels, between 0.1

[7] The negative binomial distribution is the probability distribution of the number of trial needed to get a fixed number of success. It has two parameters: the number of successes and the success probability. So, if the probability of getting a single packet transmitted is p (or pdr) then the negative binomial distribution relates this to n-packet messages as n trials. Specifically, the probability that r^{th} success (r^{th} packet gets transmitted successfully) occurs on the x^{th} try=C(x-1,r-1)p^r(1-p)^(x-r), where C is the binomial coefficient

and 2.5; the Cop message data rate having 7 levels between 16.0 kilobytes per second and 533 kilobits per second, the presence of unmanned aerial vehicles (UAVs) to serve as reconnects varied between 0 and 8, the network density varied between 145 and 36 nodes in the 25km by 25km area, and the distance between the receiver and the sender varied based on the node pair.

In these experiments the COP update message was sent with a multicasting transmission process, this means that every node is told the message and then told to tell its neighbors. This means that a particular node can receive the message from the commander (or other central data source) directly or indirectly from an intermediate node. UAVs that are present[8] to serve as reconnects act as extra nodes that do not receive messages themselves but can act as relays for messages to hop on.

Network density relates to potential attrition. The experiments included runs with 145 nodes. Other experiments were run at ~50% of that number (72). Other experiments were run with 36 nodes. This was done in order to capture the impact of the density of nodes in the same box on the same communication networks.

The as-the-crow-flies distance between nodes is measured from a node centered in the region and are fixed at the beginning. The distance from the vehicle transmitting messages to the other nodes receiving the messages ranges from ~ 1km to 18 kilometers away in areas one and two. The range expands to 29 km in areas three and four.

It is noted that terrain has a great impact on communication systems and thus the models are specific to the terrain box. The experimental results apply to terrain box 1 (area 1).

Products: Predictive Models

A predictive model of the packet delivery ratio can be developed from data from simulation runs as shown in the figure below. The logit function is convenient because it produces a value between 0 and 1. It is defined as logit(p) := log ($\frac{p}{1-p}$). Once a model for the logit(PDR) is determined, the actual PDR (labeled p) is calculated as follows:

$$p = \frac{\exp(\log it(p))}{(\exp(\log it(p)) + 1}.$$

Logit (PDR) = β_0 +

β_1(Frequency)+β_2(UAVs)+… } Other First-Order Terms

β_3(Frequency×UAVs)+… } Other Second-Order Terms

Other Higher Order Interactions

Figure 21: Generic Form of Metamodel

Before proceeding, it is important to assess whether or not simulation experiment data is amenable to being fit to such a closed form expression. A simpler model of averaged[9] performance was fit via regression for area 2 (25km by 25km) and area 3 (40 km by 40km). The plots, shown below, suggest a good fit. Similar results were observed

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[8] The UAVs present in the experiments are placed in a diamond formation in the box.

[9] By averaged, it is meant that distances between communication nodes specific node pairs is not a parameter, i.e., distance between node-pairs is not considered as a factor

for models of end-to-end delay. The fits were only slightly improved if five-parameter interactions were captured, which resulted in r-square value of approx. 0.91.

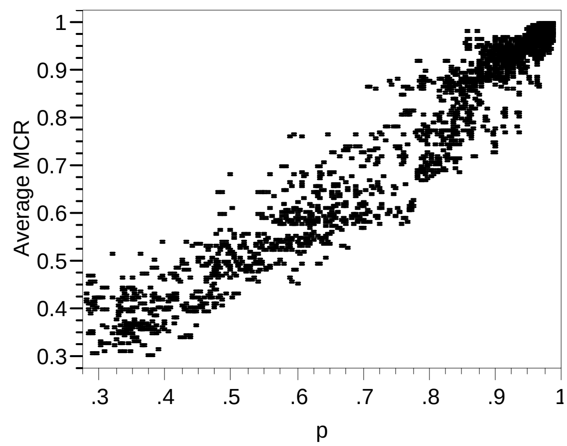

Figure 22: Area 2 "Averaged" Model for Packet Delivery Ratio Two Way Interactions r-square values of 0.896

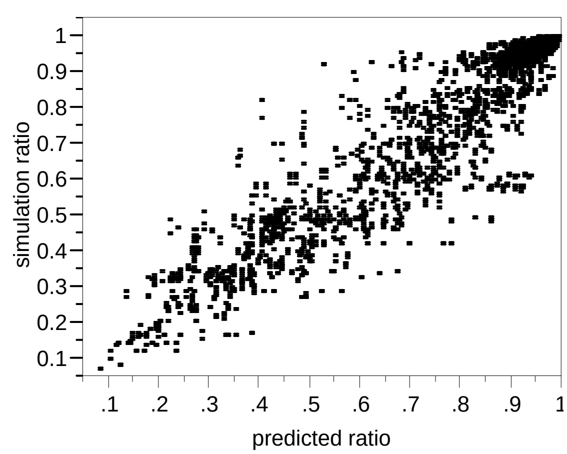

Figure 23: Area 3 "Averaged" Model for Packet Delivery Ratio (R-square is 0.86) Capturing up to Two-parameter Interactions

Appendix A provides models for all four areas. These models were not created with the averaged data but rather with node-pair-specific data. Thus, distance between a particular node pair is a factor in the models. The r-square values are shown in the table below.

Table 2: Evaluating The Fits for 2-way Parameter Interaction

Area / Equation	Adj. R-Square Value for PDR	Adj. R-Square Value for Delay
1	0.715	0.755
2	0.749	0.817
3	0.725	0.813
4	0.706	0.800

Note: The fits could have been slightly improved by representing the four-way parameter interaction in the model. An even better fit was achieved by adding an additional factor called LOS that represents the degree of "connectivity" associated with individual nodes based on its line-of-sight with other nodes. LOS was examined for Areas 2 and 3.

Table 3: Evaluating the Fits for 4-way Parameter Interaction

Area Equation	Adj. R-Square Value for PDR	Adj. R-Square Value for Delay	Adj. R-Square Value for PDR, LOS	Adj. R-Square Value for Delay, LOS
1	0.72	0.78	-	-
2	0.75	0.84	0.77	0.85
3	0.73	0.84	0.78	0.86
4	0.71	0.82	-	-

Interpreting The Results

Analysis using the models synthesized (see Appendix A for details) is provided in the following subsections. One of the many observations facilitated by the synthesized models is the critical role of dedicated UAVs for communication relay and connectivity.

Contour plots are shown below that use data from simulations of area 3. These contour plots are taken from the data generated through thousands of simulation experiments. On one axis is the distance between a potential sender and receiver. On the other access is a measure of the connectivity of line-of-sight between two such nodes. A high value (e.g., 1) suggests that the line-of-sight is blocked. In the figures, the area in the lower left corner represents communication that is short in distance and enjoys a clear line of sight. Intuitively, performance here should be better than in the upper right hand area where distances are longer and line-of-sight is more blocked.

As shown in Figure 25, with no UAVs, performance is poor for many node pairs, especially those that don't enjoy the short distance and relatively good line of sight with neighboring nodes. In Figure 26, many of the node pairs that were situated poorly (e.g., ones that are distant and have poor line of sight with neighboring nodes) now operate with much improved performance.

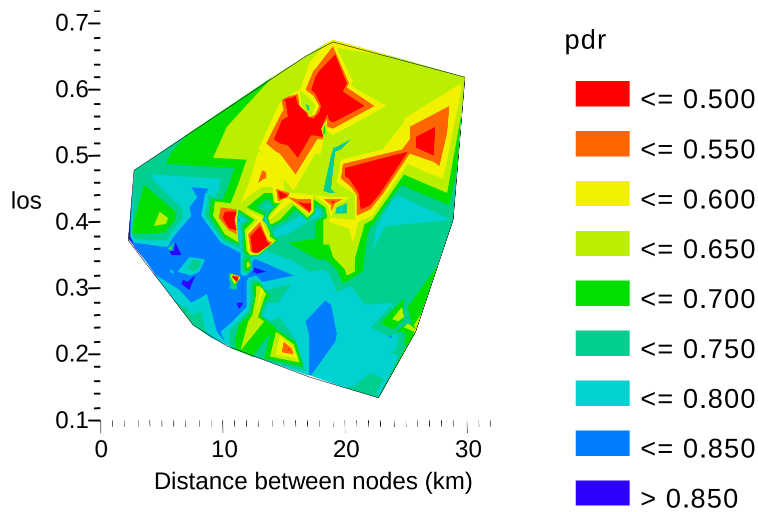

Figure 24: Performance with 0 UAVs (packet delivery ratio) given distance and line-of-sight measure for Area 3

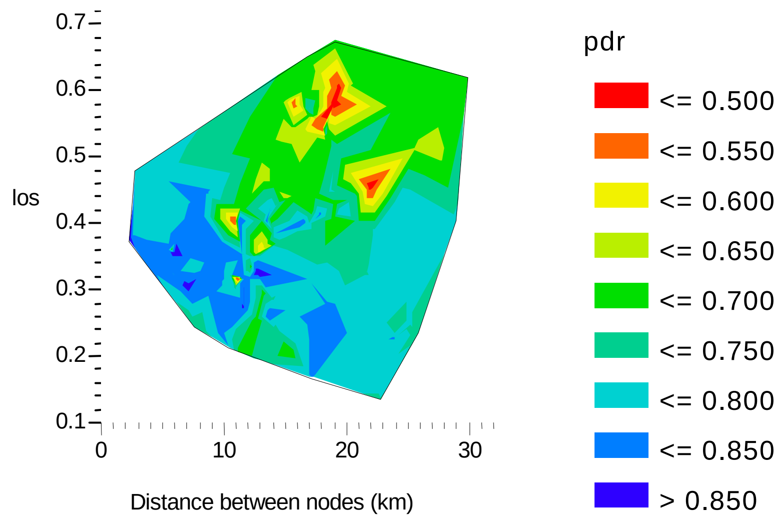

Figure 25: Performance with 8 UAVs (packet delivery ratio) given distance and line-of-sight measure for Area 3

Other selected observations are described as follows.

High Radio User Throughputs Help

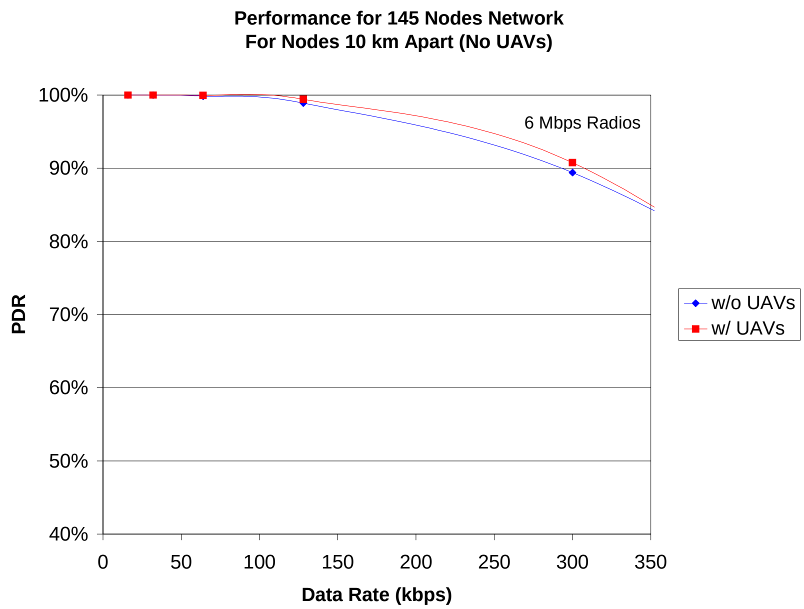

Figure 26: Area 1 Results with High User Throughput Radios

Communication performance shown in Figure 27 is strong. This is because the radio modeled are using a high user throughput (6 Mbps), high power radio (62 dbm). As a baseline, the JTRS radio cluster 1 user throughput will be 2 Mbps (maximum). The remainder of this section will use synthesized models that assumed a network of 2Mbps radios at a transmit power of 43dBM.

In contrast, simulations results (below) with 2 Mbps radios are not as good across all data rates as the higher user throughput radios. Figure 28 shows results using radios with radio power of 20 W (43 dbm). The performance degrades with data rate more significantly.

Key Advantages at Certain Frequencies

The raw data shows that frequency agility, i.e., the ability to selectively transmit at various frequencies, is important.

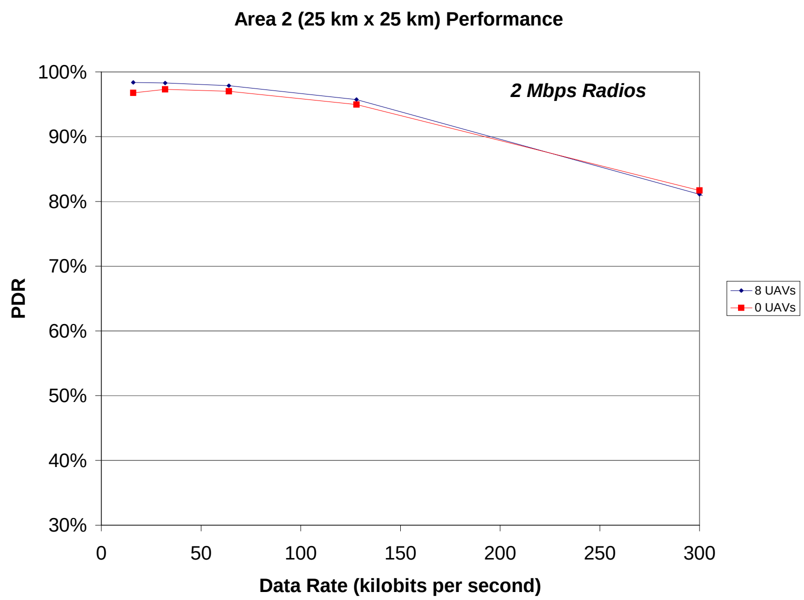

Figure 27: Impact of UAVs in Area 2 at f=0.4 GHz

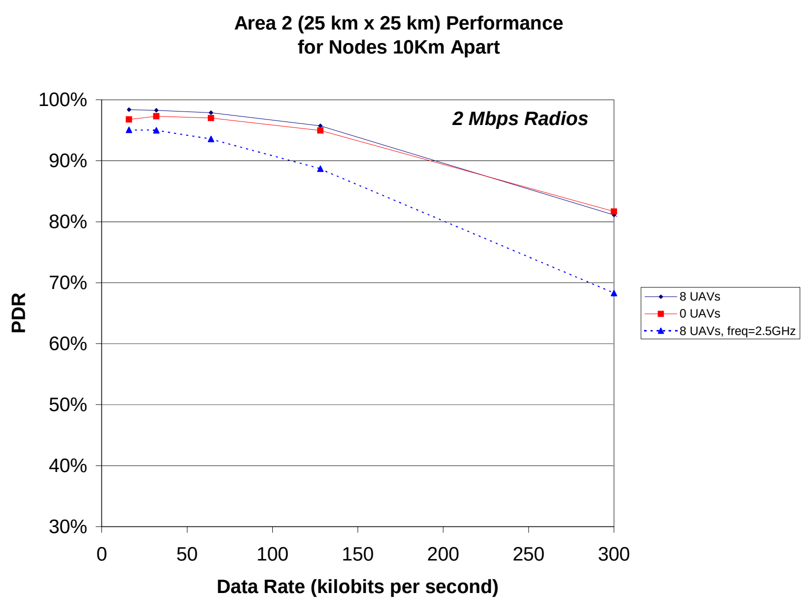

Figure 28: Frequency Has An Impact on Performance

Figure 29 shows that performance at 2.5 GHz is significantly lower than at .4 GHz (Figure 5.30). The reason for this is explained concisely in Vanderau et al (1998) as follows: The way a radio signal propagates through the airwaves is different at higher frequencies (F) than at lower ones. Signal loss between a radio transmitter and receiver increases with frequency, e.g. the loss is proportional to $1/F^2$. Quoting: “While all radio waves tend to move in straight lines, higher frequencies are blocked more sharply by terrain or buildings”. Generally speaking, as frequency increases, radio coverage decreases. This is not always detrimental as a decreased range can translate into decreased interference in a dense network. In fact higher frequencies are more difficult to detect. However, UAVS did improve capabilities at this frequency. Because channels at 2.5GHz and higher are likely more available in terms of spectrum constraints, performance issues at these and higher frequencies cannot be ignored.

To get an idea of the performance impact of various factors, the table below varies key factors and reports on the maximum data rate achievable while maintaining a 90% packet delivery ratio. Note: table used models of average performance.

Table 4: Results From a Sample of Experiments

Area	# of UAVs	Density Nodes/km^2	Frequency	90% PDR Data Rate
2 (25 x25)	8	.12	2.5 GHz	270 Kbps
2 (25 x25)	4	.12	2.5 GHz	255 Kbps
2 (25 x25)	0	.12	2.5 GHz	240 Kbps
2 (25 x25)	8	.12	0.4 GHz	320 Kbps
2 (25 x25)	4	.12	0.4 GHz	345 Kbps
2 (25 x25)	0	.12	0.4 GHz	375 Kbps
2 (25 x25)	8	.06	2.5 GHz	110 Kbps
2 (25 x25)	4	.06	2.5 GHz	40 Kbps
2 (25 x25)	0	.06	2.5 GHz	-

Note: Data rate capability impacts the size of the COP message and the frequentness of the COP’s dissemination

UAVs Are Critical for Less Dense Networks

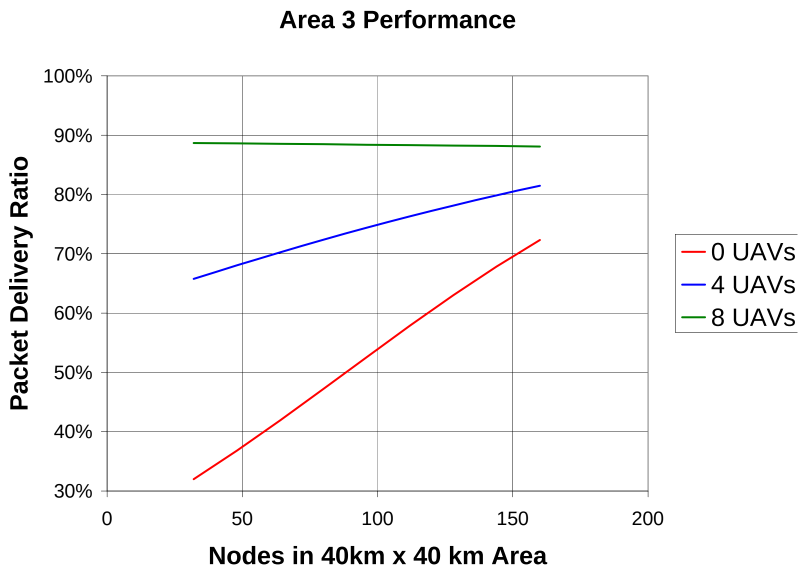

Figure 29: Impact of UAVs is Pronounced Especially for Sparse Forces

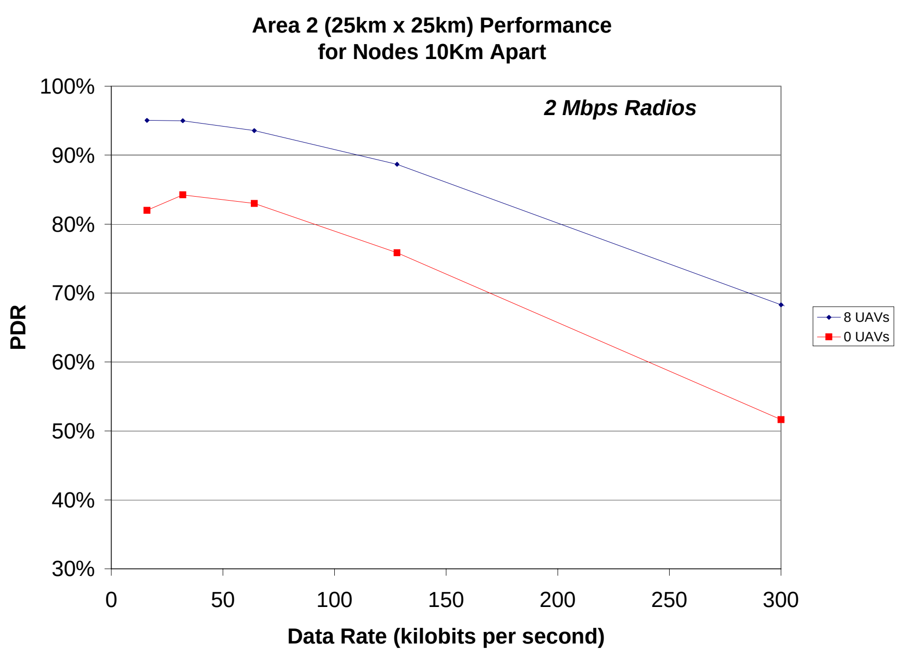

Figure 30: Impact of UAVs

5. What the Models Tell Us

The meta-models presented follow intuition in some respects:

(1) Data rate drives the performance. Depending on other parameters, network performance will degrade precipitously at a certain level of offered traffic.

(2) Higher network density and the presence of UAVs increase the likelihood of a message being completed.

(3) While high data rates start to tax a network at some level, larger distances between nodes and high signal frequencies decrease likelihood of messages getting through and increase end-to-end delay.

Other observations:

(4) The presence of UAVs help network performance, especially for the transmission at higher signal frequencies. However, there is a limit to the number of additional UAVs that enhance performance; too many can hurt network performance. UAVS help when they are needed but could be a nuisance;

(5) Other factors (e.g. network density) and technologies (e.g., frequency agile radios, SATCOM, etc.) may obviate the need for large numbers of UAVs at the tactical level.

6. Observations and Conclusions

The U.S. Army is developing a fighting force intended to be deployable, rapid-reacting, lethal, and, foremost, able to maintain situation awareness and responsiveness to a degree that it can shape the battlefield and chose the battles where it may apply overwhelming force. Superior C4ISR will be required. This study has developed a framework for analyzing the marginal impact of communication technology and architectural options for the future force.

At the tactical level (brigade and below), the performance of the C4ISR or battle command network is highly sensitive to technology detail and scenario specifics. Terrain plays a large role. Antenna size and type, radio frequency, and mobility all have significant impacts on technical performance in terms of connectivity, delays and message completion rates. Communication network simulation runs were used to synthesize meta-models to capture communication performance. Analysis using the models thus far has yielded some preliminary observations that are summarized as follows: (1) High capacity radios for future forces will be very important towards good performance (> 5 Mbps user throughput); however, spectral availability issues are key towards higher data rate radios (see Joe and Porche (2004)) and will be a limiting factor. (2) This suggests the importance and advantage of future concepts like frequency agile, cognitive radios. (3) Near future radios (limited to 1-2 Mbps user throughputs) on vehicles will require significant UAV presence to ensure reliable situational awareness network performance. This is especially relevant if smaller forces are expected to be responsible for larger and larger areas of operation.

7. Discussion: On-going and Future Work

These analyses have provided insight into battlefield network communications performance parameters. Only a handful of factors of interest were considered but the analysis provided a possible template for modeling data of this type in future simulation efforts. The scope will expand to more variables of impact to explore and more complicated scenarios. Hopefully the models described above will easily expand as these are added to the variable list, but continued diagnostics are needed to ensure that the proper model is being fit to the data.

When these models are inserted into force-on-force simulation exercises, questions related to the impact of communication on operations will be addressable. For example: (1) What is the marginal impact of UAV assets on warfighter effectiveness? What is the robustness of the situational awareness network for a given force and a given area of operation?

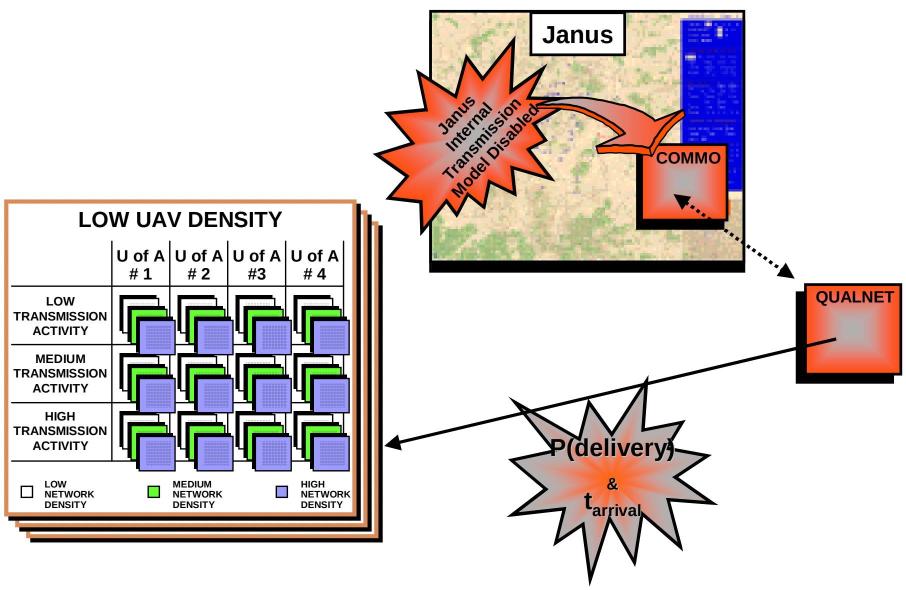

Figure 31: Next Step: QUALNET Derived Model Inserted in Combat Simulator

This figure is a more detailed overview of the project's goals for interfacing a force-on-force simulator (e.g., Janus) with the communication meta-model developed through Qualnet. A set of experiments will be conducted with the force-on-force combat simulator using all four terrain boxes with various levels of message transmission activity as well as different nodal density levels and different numbers of UAVs.

Appendix

Appendix A. Communication models for Terrains

The closed form expressions described in this appendix represent models of communication for areas one through four. The factors of interest in the models are

- Frequency (f)
- Radio power (p)
- Density (d)
- Data rate (rt)
- Number of UAVs (u)
- Distance between node pairs (ds)

The responses modeled are

- Packet delivery ratio (PDR)
- End to end delay (delay)

The four models described were fit via regression analysis using data from numerous simulation runs using Qualnet. Specifically, the data were fit to the logit function of the packet delivery ratio and the log of the end to end delay. The adjusted r-squared values are shown in Table A.1.

Table A.1: Evaluating the fits for 2-way parameter interaction

Area/Equation	R-Square Value for PDR	R-Square Value for Delay
1	0.715	0.755
2	0.749	0.817
3	0.725	0.813
4	0.706	0.800

Note: The fits can be improved by representing more than two-way parameter interaction in the model.

The expression for a logit function is shown below.

$$\text{logit}(p) := \log\left(\frac{p}{1-p}\right)$$

Since the regression analysis creates a model of the logit(pdr), the value of the pdr is the inverse logit function. Thus, the inverse logit is of use for this research effort. It is below.

$$p = \frac{\exp(\log it(p))}{(\exp(\log it(p)) + 1}$$

The generic form of the meta-models being described in this section take the following form:

$$\text{Logit (PDR)} = \beta_0 +$$

$$\beta_1(\text{Distance}) + \beta_2(\text{Powewr}) + \ldots \left\{ \begin{array}{c} \text{Other} \\ \text{First-Order} \\ \text{Terms} \end{array} \right.$$

$$\beta_3(\text{Distance} \times \text{UAVs}) + \ldots \left\{ \begin{array}{c} \text{Other} \\ \text{Second-Order} \\ \text{Terms} \end{array} \right.$$

Other Higher Order Interactions

The equations' formats can be generalized with the coefficients labeled o1 through 07 and β0 through β28 as follows.

Table A.2: Format of Data tables

Term	Estimate
Intercept	β0
ds	β1
p	β2
(ds-o1)*(p-o2)	β3
f	β4
(ds-o1)*(f-o3)	β5
(p-o2)*(f-o3)	β6
d	β7
(ds-o1)*(d-o4)	β8
(p-o2)*(d-o4)	β9
(f-o3)*(d-o4)	β10
u	β11
(ds-o1)*(u-o6)	β12
(p-o2)*(u-o6)	β13
(f-o3)*(u-o6)	β14
(d-o4)*(u-o6)	β15
rt	β16
(ds-o1)*(rt-o5)	β17
(p-o2)*(rt-o5)	β18
(f-o3)*(rt-o5)	β19
(d-o4)*(rt-o5)	β20
(u-o6)*(rt-o5)	β21
log(rt)	β22
(ds-o1)*(log(rt)-o7)	β23
(p-o2)*(log(rt)-o7)	β24
(f-o3)*(log(rt)-o7)	β25
(d-o4)*(log(rt)-o7)	β26
(u-o6)*(log(rt)-o7)	β27
(rt-o5)*(log(rt)-o7)	β28

So that the complete, generalized expression is

logit(pdr) = β0 + ds*β1 + p*b2 + (ds-o1)*(p-o2)*β3 + f*β4 + (ds-o1)*(f-o3)*β5 + (p-o2)*(f-o3)*β6 + d*β7 + (ds-o1)*(d-o4)*β8 + (p-o2)*(d-o4)*β9 + (f-o3)*(d-o4)*β10 + u* β11 + (ds-o1)*(u-o6)*β12 +(p-o2)*(u-o6) * β13 + (f-o3)*(u-o6)*β14 + (d-o4)*(u-o6) * β15 + rt*β16 + (ds-o1)*(rt-o5)*β17 + (p-o2)*(rt-o5)*β18 + (f-o3)*(rt-o5)*β19 +(d-o4)*(rt-o5)* β20 + (u-o6)*(rt-o5)*β21 +log(rt)* β22 + (ds-o1)*(log(rt)-o7)* β23 +(p-o2)*(log(rt)-o7)* β24+(f-o3)*(log(rt)-o7)*β25 + (d-o4)*(log(rt)-o7)* β26 +(u-o6)*(log(rt)-o7)* β27 +(rt-o5)*(log(rt)-o7)*β28

where,

ds	:=	distance between node-pairs in kilometers
p	:=	radio power in Decibels
f	:=	frequency in Gigahertz
d	:=	density in nodes per square kilometers
rt	:=	data rate in kilobits per second
u	:=	number of UAVs

For example for area 1, the offset coefficients (*o**) are

- *o1* = 9.74145
- *o2* = 45.8749
- *o3* = 1.12383
- *o4* = 0.17633
- *o5* = 199.708
- *o6* = 4.09479
- *o7* = 4.71089

The equations presented above are presented below in a more readable form in the tables below.

Table A.3: Area 1 (PDR)

Term	Estimate
Intercept	-7.460954811
ds	-0.144115681
p	0.012725538
(ds-9.74145)*(p-45.8749)	0.000326067
f	-0.429489956
(ds-9.74145)*(f-1.12383)	-0.016828023
(p-45.8749)*(f-1.12383)	0.002651833
d	-2.448472093
(ds-9.74145)*(d-0.17633)	0.352169843
(p-45.8749)*(d-0.17633)	-0.009337938
(f-1.12383)*(d-0.17633)	1.908550936
u	0.000494488
(ds-9.74145)*(u-4.09479)	-0.004318525
(p-45.8749)*(u-4.09479)	5.3355E-05
(f-1.12383)*(u-4.09479)	0.010854036
(d-0.17633)*(u-4.09479)	-0.012043543
rt	-0.037766834
(ds-9.74145)*(rt-199.708)	8.58345E-05
(p-45.8749)*(rt-199.708)	-3.92614E-05
(f-1.12383)*(rt-199.708)	0.000651289
(d-0.17633)*(rt-199.708)	0.03548329
(u-4.09479)*(rt-199.708)	2.22316E-05
log(rt)	3.494608447
(ds-9.74145)*(log(rt)-4.71089)	-0.008715956
(p-45.8749)*(log(rt)-4.71089)	0.004502034
(f-1.12383)*(log(rt)-4.71089)	-0.069481796
(d-0.17633)*(log(rt)-4.71089)	-8.424818227
(u-4.09479)*(log(rt)-4.71089)	-0.010022519
(rt-199.708)*(log(rt)-4.71089)	0.012999863

Table A.4: Area 2

Term	Estimate
Intercept	-8.718660932
ds	-0.056903123
pwr	0.011512262
(ds-9.77858)*(pwr-45.9117)	0.001044546
f	-0.505493111
(ds-9.77858)*(f-1.13673)	0.006345062
(pwr-45.9117)*(f-1.13673)	0.003332478
d	-1.120487986
(ds-9.77858)*(d-0.17612)	0.194697425
(pwr-45.9117)*(d-0.17612)	0.000743776
(f-1.13673)*(d-0.17612)	1.593317154
u	0.011344108
(ds-9.77858)*(u-4.03852)	-0.001534965
(pwr-45.9117)*(u-4.03852)	-0.000373762
(f-1.13673)*(u-4.03852)	0.024318625
(d-0.17612)*(u-4.03852)	-0.104387249
rt	-0.039274128
(ds-9.77858)*(rt-199.098)	9.33325E-05
(pwr-45.9117)*(rt-199.098)	-2.16774E-05
(f-1.13673)*(rt-199.098)	0.00125172
(d-0.17612)*(rt-199.098)	0.028577504
(u-4.03852)*(rt-199.098)	0.000200101
log(rt)	3.657781759
(ds-9.77858)*(log(rt)-4.70151)	-0.017403707
(pwr-45.9117)*(log(rt)-4.70151)	0.00044408
(f-1.13673)*(log(rt)-4.70151)	-0.039626276
(d-0.17612)*(log(rt)-4.70151)	-7.679328346
(u-4.03852)*(log(rt)-4.70151)	-0.050693625
(rt-199.098)*(log(rt)-4.70151)	0.013374708

Table A.5: Area 3

Term	Estimate
Intercept	-5.855816349
ds	-0.043061243
p	0.026390456
(ds-15.6968)*(p-46.0043)	0.001218131
f	-0.732197524
(ds-15.6968)*(f-1.10713)	-0.018696361
(p-46.0043)*(f-1.10713)	0.017039565
d	-2.505611768
(ds-15.6968)*(d-0.0694)	0.449824114
(p-46.0043)*(d-0.0694)	0.008519344
(f-1.10713)*(d-0.0694)	-0.264137436
u	0.03056635
(ds-15.6968)*(u-4.1808)	0.002540722
(p-46.0043)*(u-4.1808)	-0.000298798
(f-1.10713)*(u-4.1808)	0.029593653
(d-0.0694)*(u-4.1808)	-0.021669586
rt	-0.031050663
(ds-15.6968)*(rt-193.92)	3.63672E-05
(p-46.0043)*(rt-193.92)	-1.49386E-05
(f-1.10713)*(rt-193.92)	0.000170988
(d-0.0694)*(rt-193.92)	0.076478561
(u-4.1808)*(rt-193.92)	0.000173894
log(rt)	2.592817848
(ds-15.6968)*(log(rt)-4.65234)	0.001334408
(p-46.0043)*(log(rt)-4.65234)	0.000203602
(f-1.10713)*(log(rt)-4.65234)	0.11811913
(d-0.0694)*(log(rt)-4.65234)	-19.22459429
(u-4.1808)*(log(rt)-4.65234)	-0.051854286
(rt-193.92)*(log(rt)-4.65234)	0.010221632

Table A.6: Area 4

Term	Estimate
Intercept	-14.62324806
ds	-0.064477288
p	0.021111431
(ds-15.603)*(p-45.9308)	0.001242567
f	-0.719757973
(ds-15.603)*(f-1.12139)	-0.026085271
(p-45.9308)*(f-1.12139)	0.012033069
d	-4.978306236
(ds-15.603)*(d-0.06935)	0.360854673
(p-45.9308)*(d-0.06935)	-0.034237073
(f-1.12139)*(d-0.06935)	1.818415375
u	0.011592061
(ds-15.603)*(u-4.11415)	-0.000413265
(p-45.9308)*(u-4.11415)	0.000243691
(f-1.12139)*(u-4.11415)	0.023445527
(d-0.06935)*(u-4.11415)	0.074051142
rt	-0.047424143
(ds-15.603)*(rt-202.384)	3.93345E-05
(p-45.9308)*(rt-202.384)	-3.37799E-05
(f-1.12139)*(rt-202.384)	0.001119479
(d-0.06935)*(rt-202.384)	0.094306311
(u-4.11415)*(rt-202.384)	0.000223639
log(rt)	5.10630156
(ds-15.603)*(log(rt)-4.73631)	0.002496818
(p-45.9308)*(log(rt)-4.73631)	0.001259071
(f-1.12139)*(log(rt)-4.73631)	0.023213712
(d-0.06935)*(log(rt)-4.73631)	-23.59392878
(u-4.11415)*(log(rt)-4.73631)	-0.057065023
(rt-202.384)*(log(rt)-4.73631)	0.016656656

This remainder of this appendix considers models of delay for the four areas. First equations (Two way parameter interactions) are presented. Then, more easily read tables.

Table A. 7 Area 1 (delay)

Term	Estimate
Intercept	7.86836702
ds	0.064094049
p	-0.001833424
(ds-9.74145)*(p-45.8749)	-9.8375E-05
f	-0.028244187
(ds-9.74145)*(f-1.12383)	0.010371765
(p-45.8749)*(f-1.12383)	0.009617641
d	6.212019798
(ds-9.74145)*(d-0.17633)	0.060655473
(p-45.8749)*(d-0.17633)	-0.010551809
(f-1.12383)*(d-0.17633)	-0.038620384
u	0.010069665
(ds-9.74145)*(u-4.09479)	0.003336211
(p-45.8749)*(u-4.09479)	-0.000571154
(f-1.12383)*(u-4.09479)	0.035373902
(d-0.17633)*(u-4.09479)	0.154023307
rt	0.031169005
(ds-9.74145)*(rt-199.708)	-3.61293E-05
(p-45.8749)*(rt-199.708)	6.45355E-05
(f-1.12383)*(rt-199.708)	-0.001864404
(d-0.17633)*(rt-199.708)	-0.008542553
(u-4.09479)*(rt-199.708)	3.33072E-05
log(rt)	-3.389648479
(ds-9.74145)*(log(rt)-4.71089)	0.015538759
(p-45.8749)*(log(rt)-4.71089)	-0.005680486
(f-1.12383)*(log(rt)-4.71089)	0.034004137
(d-0.17633)*(log(rt)-4.71089)	4.43820331
(u-4.09479)*(log(rt)-4.71089)	0.012292536
(rt-199.708)*(log(rt)-4.71089)	-0.010551076

Table A.8 Area 2 (delay)

Term	Estimate
Intercept	9.447350375
ds	0.021980792
pwr	0.00165042
(ds-9.77858)*(pwr-45.9117)	-0.00026741
f	-0.417104768
(ds-9.77858)*(f-1.13673)	-0.001437661
(pwr-45.9117)*(f-1.13673)	-0.000127332
d	5.807506024
(ds-9.77858)*(d-0.17612)	0.020307046
(pwr-45.9117)*(d-0.17612)	0.013365543
(f-1.13673)*(d-0.17612)	-1.413568285
u	-0.002370652
(ds-9.77858)*(u-4.03852)	0.000399796
(pwr-45.9117)*(u-4.03852)	-8.73275E-05
(f-1.13673)*(u-4.03852)	0.00780889
(d-0.17612)*(u-4.03852)	0.052039242
rt	0.031877858
(ds-9.77858)*(rt-199.098)	-2.01532E-05
(pwr-45.9117)*(rt-199.098)	2.66785E-05
(f-1.13673)*(rt-199.098)	-0.002102359
(d-0.17612)*(rt-199.098)	-0.017390916
(u-4.03852)*(rt-199.098)	3.38665E-05
log(rt)	-3.544955405
(ds-9.77858)*(log(rt)-4.70151)	0.008138538
(pwr-45.9117)*(log(rt)-4.70151)	-0.000118306
(f-1.13673)*(log(rt)-4.70151)	-0.114310292
(d-0.17612)*(log(rt)-4.70151)	5.062926232
(u-4.03852)*(log(rt)-4.70151)	0.004863214
(rt-199.098)*(log(rt)-4.70151)	-0.011557246

Table A.9 Area 3 (delay)

Term	Estimate
Intercept	2.810766594
ds	0.024061631
p	-0.000376741
(ds-15.6968)*(p-46.0043)	-0.000233977
f	-0.244775334
(ds-15.6968)*(f-1.10713)	-0.002667492
(p-46.0043)*(f-1.10713)	-0.00113474
d	16.66138395
(ds-15.6968)*(d-0.0694)	0.019501425
(p-46.0043)*(d-0.0694)	0.005022948
(f-1.10713)*(d-0.0694)	-4.226402786
u	-0.008612198
(ds-15.6968)*(u-4.1808)	-0.000612673
(p-46.0043)*(u-4.1808)	-0.000334472
(f-1.10713)*(u-4.1808)	0.006607612
(d-0.0694)*(u-4.1808)	0.479712655
rt	0.018894808
(ds-15.6968)*(rt-193.92)	-1.78761E-05
(p-46.0043)*(rt-193.92)	4.59345E-05
(f-1.10713)*(rt-193.92)	-0.002494839
(d-0.0694)*(rt-193.92)	0.029154407
(u-4.1808)*(rt-193.92)	3.53694E-05
log(rt)	-1.939976307
(ds-15.6968)*(log(rt)-4.65234)	0.004324752
(p-46.0043)*(log(rt)-4.65234)	-0.002663753
(f-1.10713)*(log(rt)-4.65234)	0.028002515
(d-0.0694)*(log(rt)-4.65234)	4.698102582
(u-4.1808)*(log(rt)-4.65234)	0.006634126
(rt-193.92)*(log(rt)-4.65234)	-0.006094104

Table A.10 Area 4 (delay)

Term	Estimate
Intercept	10.48802137
ds	0.025672549
p	1.59363E-05
(ds-15.603)*(p-45.9308)	-0.00028144
f	-0.239425078
(ds-15.603)*(f-1.12139)	0.010371208
(p-45.9308)*(f-1.12139)	0.004645574
d	15.32668466
(ds-15.603)*(d-0.06935)	0.146743028
(p-45.9308)*(d-0.06935)	-0.006239019
(f-1.12139)*(d-0.06935)	-2.12234659
u	0.011929188
(ds-15.603)*(u-4.11415)	0.001463114
(p-45.9308)*(u-4.11415)	-5.55474E-05
(f-1.12139)*(u-4.11415)	0.024330278
(d-0.06935)*(u-4.11415)	0.021202838
rt	0.034251733
(ds-15.603)*(rt-202.384)	-2.83939E-05
(p-45.9308)*(rt-202.384)	5.57673E-05
(f-1.12139)*(rt-202.384)	-0.00199673
(d-0.06935)*(rt-202.384)	-0.034404391
(u-4.11415)*(rt-202.384)	7.17362E-05
log(rt)	-3.953824206
(ds-15.603)*(log(rt)-4.73631)	0.004869515
(p-45.9308)*(log(rt)-4.73631)	-0.002830166
(f-1.12139)*(log(rt)-4.73631)	-0.061591662
(d-0.06935)*(log(rt)-4.73631)	12.66271853
(u-4.11415)*(log(rt)-4.73631)	0.005611116
(rt-202.384)*(log(rt)-4.73631)	-0.011938993

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