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MODELING THE WIRELESS NETWORK ARCHITECTURE OF LAND WARRIOR

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ABSTRACT

The United States Army is designing and implementing a revolutionary advance in the combat power of individual infantrymen on the battlefield: Land Warrior. In Land Warrior, each soldier becomes a node in a wireless local area network (WLAN). In order to account for likely losses of line of site between soldiers, the On Demand Multicast Routing Protocol (ODMRP) is used. The purpose of this research was to construct a simulation study to determine whether the communications architecture of Land Warrior was sufficiently scalable to use in large Army units. This paper describes the input analysis conducted to determine probability distributions used to generate message traffic. This paper also describes the development of the simulation model used to determine the scalability of the Land Warrior communications architecture.

1 INTRODUCTION

The United States Army is designing and implementing a revolutionary advance in the combat power of individual infantrymen on the battlefield. This system, known as Land Warrior, involves linking soldiers through the use of IEEE 802.11b technology. Land Warrior provides enhanced situational awareness and lethality. Prototype systems have been tested with up to a platoon of soldiers (approximately forty soldiers) (Dismounted Battle Laboratory 1999).

In order to account for likely losses of line of site between soldiers, the On Demand Multicast Routing Protocol (ODMRP) (Lee et al. 1999) is used in the Land Warrior radios. ODMRP rides on top of IEEE 802.11b. ODMRP involves the use of multicast packets to create routes between nodes. These nodes can expire after a specified time or they can be made invalid when a packet sent along a route fails to reach its intended destination. As a result, the protocol itself consumes some of the available bandwidth.

As shown in Figure 1, infantry squads are grouped into platoons and companies. These companies use the same "channel." The communications within a Land Warrior-equipped company is referred to as a "company cloud." In the future, as battlefields become less linear in nature, there will be many ad hoc interactions between company clouds. Though the packets from one company cloud are not visible at the application layer in other company clouds, those packets must be processed at lower layers in the protocol stack. Between this interference (and its resultant degradation of effective bandwidth) and the overhead associated with ODMRP, the fundamental question of this work is whether the communications architecture of Land Warrior will be capable of supporting combat operations of an entire infantry division.

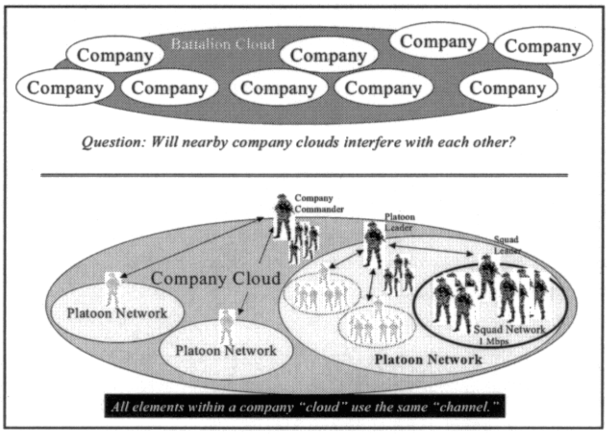

Figure 1: The Topology of the Land Warrior Network

The purpose of this research was to construct a simulation study to determine whether the communications architecture of Land Warrior was sufficiently scalable to use in large Army units. This simulation study involved detailed input analysis of data gathered during training exercises with Land Warrior prototype systems. It also involved the detailed modeling of the Mesh Radio (the

Land Warrior radio using the ODMRP) in OpNet (OpNet Technologies 2001). An Army entity-level, constructive simulation will be used to create movement paths for soldiers during a simulation of a tactical mission. These movement paths will then be used in OpNet to stimulate the ODMRP. Finally, OpNet simulation experiments of gradually increasing complexity will be conducted to determine whether Land Warrior's communications architecture will support an Army infantry division (approximately 12,000 soldiers).

2 OVERALL DESIGN

This research project consisted of five phases. Phase 1 involved the modeling of the Land Warrior 0.6 prototype system for a rifle platoon. Phase I was completed in FY01. Phase II involved the modeling of the Mesh Radio implementation of ODMRP for use within OPNET. Phases I and II also involved detailed input analysis of exercise data to produce probability distributions for generating message traffic in the simulation. Phase III involved the integration of the Mesh Radio model into the existing platoon model to verify that a platoon should be able to communication using Mesh radio. Phase IV will involve the use of an Army constructive simulation to script the paths of the infantry soldiers fighting a battle. Phase V will involve the use of the Phase IV script to have the entities in OpNet using Land Warrior move across the terrain. The resulting losses of line of site due to entity movement will stimulate the ODMRP to find new routes. In Phase V, the size of the simulation will be gradually increased until a full division is being simulated.

3 INPUT ANALYSIS

Developmental tests of the Land Warrior system were conducted in 1999 with a platoon (approximately 40 soldiers) from the 82nd Airborne Division conducting tactical operations at Fort Polk, Louisiana. This data, the only data available, was used to generate the input distributions for the Land Warrior communications simulations. The data gathered during these experiments posed a number of problems for statistical analysis. There was not enough of it. While there were thousands of packets, these packets were gained from three different training scenarios and there was no data for units larger than platoons. Raw network packet data was unavailable; the data provided had been "cleaned up," and some important information may have been lost. (Packets deemed to be erroneous, duplicate entries, etc. had been removed.) Because the equipment was new to the soldiers, it is probable that use of Land Warrior – and hence the message traffic generated – will be quite different for trained soldiers after the system is deployed.

In 2001, the project team attempted to use traditional statistical analysis techniques to determine probability distributions to use as traffic generators in the simulation model (Hall et al. 2001). While common statistical methods suggested probability distributions, in almost all cases these distributions failed the Chi-Square, Anderson-Darling, and Kolmogornov-Smirnov goodness-of-fit tests. A new method of statistical analysis was needed.

3.1 Bootstrapping Techniques for Statistical Analysis

The movement toward technological and computer-based statistics is transforming the field. Statisticians are relying less on "theoretical sampling distributions such as $\chi 2$, t, and F, whose appropriateness for any given problem always rests on untestable assumptions" (Hamilton 1992). Instead of using these methods, statisticians are using a method called bootstrapping, proposed by Bradley Efron in early 1980s, which involves using data at hand to construct appropriate sampling distributions empirically (Hamilton 1992).

Bootstrapping, similar to Monte Carlo experiments, requires a large number of rapid calculations – performed by computers – to create data samples from the actual data, rather than from parameters that might describe the data sample. "Basically we bootstrap a sample size of n by drawing many random samples, each of them also size n, choosing cases from the original sample with replacement."(Hamilton 1992)

Figure 2 shows a general diagram of the bootstrap method for analyzing statistical accuracy. Observed data,

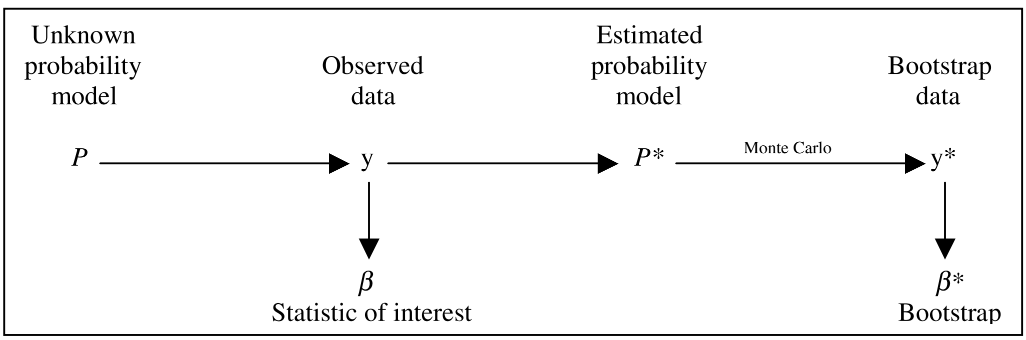

Figure 2: A General Diagram of the Bootstrap Method for Assessing Statistical Accuracy

y, is gathered from some real, unknown probability model, *P*. Data *y* are used to create an estimated distribution, *P**. Data is generated according to *P** to use in the experiment or simulation. The ideas behind bootstrapping are quite useful when conducting linear regression; however, they can also be employed when conducting basic distribution estimation. In fact we employed this method, with some modifications, when examining the data from the Land Warrior exercise at Fort Polk.

3.2 Bootstrapping Modifications and Land Warrior

We used bootstrapping to verify our results for both discrete probability mass functions and continuous probability density functions. Specifically, we used it to verify distributions which were made up of various percentages of the random variable falling into bins of different sizes of the random variable (e.g. f(x) = 0.50x for packet size = 1 and f(x) = 0.50x for packet size = 2, where x represents the number of pieces of packet size data we have). The reason we used bootstrapping here rather than on data that fit as a combination of traditional distributions was because these distributions do not have any actual parameters we can test except mean and standard deviation, and these parameters do not necessarily describe one specific distribution when considering binned data.

A statistical package called Minitab (Minitab 2001) was used in order to create the bootstrap samples. Minitab has a random number generator which will select with replacement from a data set the number of data points the user specifies. We created samples of the same size as our original data samples. While bootstrapping typically involves over a thousand samples, we actually made a modification to this process, using only around one hundred samples for each data type, due to the rigor of sample comparison.

If there were substantial differences between the actual data sample (and its estimated distribution) and the bootstrap samples (and their estimated distributions), evidence would exist that the initial, proposed distribution for the sample may not be as accurate as desired (Hamilton 1992). This idea was used to analyze the Fort Polk data sets and proposed distributions.

3.3 Examples of Analysis

There are four main types of packets of interest in the Land Warrior network: Active Soldier, Email, Overlay, and Voice Over Internet Protocol (VOIP). Active Soldier packets, designed to be broadcast once a minute by each soldier, inform the other members of the unit of the soldier's position. Email packets are used for sending calls for fire support (i.e., artillery), request for medical evacuation, etc. Overlay packets are used to send pictures to other soldiers' displays. VOIP packets are used to transmit voice communications (like a walkie-talkie) to other soldiers in the unit. For each packet, there were two attributes of interest: size and inter-arrival time. The analysis conducted was similar for each type of packet.

Figure 3 shows that for the inter-arrival times of Email packets, the combination of two different probability distributions are needed to accurately reflect the behavior of the system. In this case, a packet was generated from f(x) with a probability of 0.5 and from g(x) with an equal probability. Figure 4 shows a histogram of observed data that were used to generate the theoretical distributions shown in Figure 3.

$$\alpha := 0.540714$$

$$\beta := 89.6443$$

$$f(x) := \begin{cases} \frac{1}{2}\cdot\left[\frac{\alpha}{\beta^{\alpha}}\cdot x^{\alpha-1}\cdot\exp\left[-1\cdot\left(\frac{x}{\beta}\right)^{\alpha}\right]\right] & \text{if } x \ge 0 \\ 0 & \text{if } x < 0 \end{cases}$$

$$g(x) := \begin{cases} \frac{1}{2}\cdot\left(\frac{1}{70-60}\right) & \text{if } 60 \le x \le 70 \\ 0 & \text{otherwise} \end{cases}$$

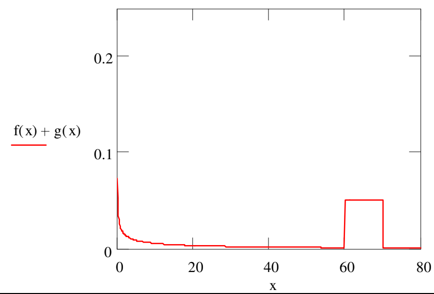

Figure 3: Theoretical Distributions Created Through Statistical Analysis

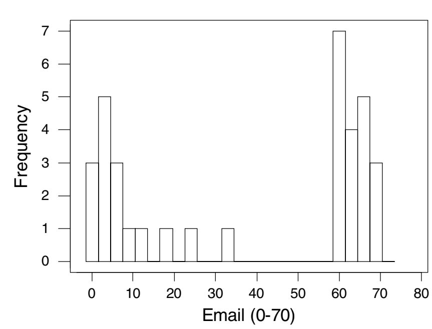

Figure 4: Histogram of Observed Data Used to Generate the Distributions Shown in Figure 3

3.4 Trimming Normal Data

Trimming data, especially to help fit symmetric distributions is quite common. For single variables, outliers are cases with extreme standard scores, say | z i | > 4 (Friendly 1995). This technique was applied for analyzing the inter-arrival times of individual soldiers' Active Soldier packets. These packets appear to follow a Weibull distribution with a shape parameter $\alpha = 0.540714$ and scale parameter $\beta = 89.6443$. This result was a bit surprising, since continuous inter-arrival data is usually modeled with an exponential distribution. The Anderson-Darling Test statistic for the Weibull was significantly better (smaller, at 1.402) than it was for the exponential distribution fit (at over 7). The highest one percent of the data and the lowest one percent of the data was trimmed, resulting in a two percent trimmed mean to go from Figure 5 to Figure 6. Figure 5 shows how well the data fit before trimming, and Figure 6 shows it after trimming.

3.5 Anomalies

During the statistical analysis, an anomaly in the prototype system was discovered. This anomaly confounded attempts to fit the data to a standard probability distribution. To account for this anomaly in the real system, the combination of two probability distributions was needed.

Recall that Active Soldier packets are supposed to be sent once a minute. The researches expected the distribution of inter-arrival times to be a normal distribution with a very tight standard deviation. Figure 7 shows a histogram of observed data. Note that in many cases a soldier sending a GPS packet after 60 seconds, then again immediately afterward, about 2 seconds later.

Figure 8 shows how the VOIP inter-arrival times behaved in an unexpected way. Though most of the packets were clustered around 0.01 seconds, a sizable number of packets were transmitted every 0.001 seconds. Again, the use of two distinct probability distributions was used to generate VOIP packets in the simulation model.

4 MODEL DESIGN

Though Mesh Radio is a significant enhancement, the packet forwarding capability of ODMRP is likely to have an adverse effect on the throughput and delay parameters of the underlying network. In order to quantify the positive and negative effects of this new protocol, an OpNet process model was developed so that a Mesh Radio-equipped Land Warrior unit could be modeled. It is important to note that the Mesh radio has some differences from ODMRP. For instance, ODMRP has mechanisms to adjust the timeout parameter associated with known routes based on knowledge of the entities' position and velocity. This does not seem to be supported in the Mesh Radio. Where differences occurred, the implementation of ODMRP in the Mesh Radio was used.

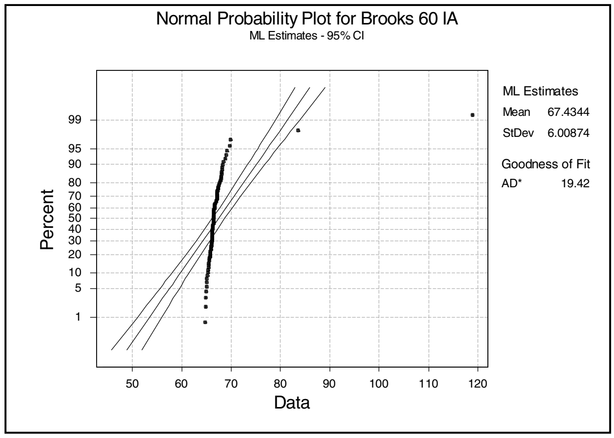

Figure 5: The Fit of the Inter-Arrival Times of Active Soldier Packets Before Trimming

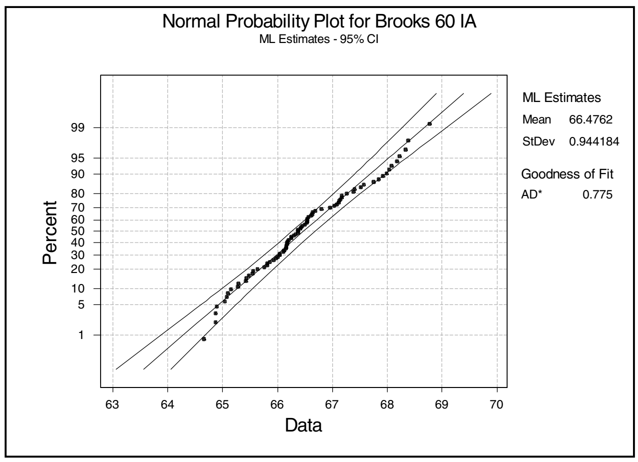

Figure 6: The Fit of the Inter-Arrival Times of Active Soldier Packets After Trimming

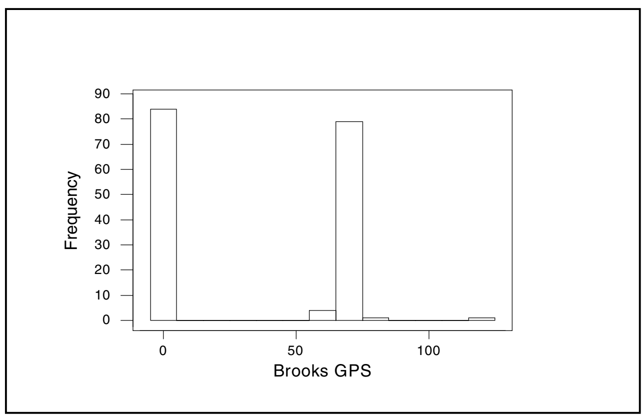

Figure 7: Histogram of Observed Data for Active Soldier Packet Inter-Arrival Times

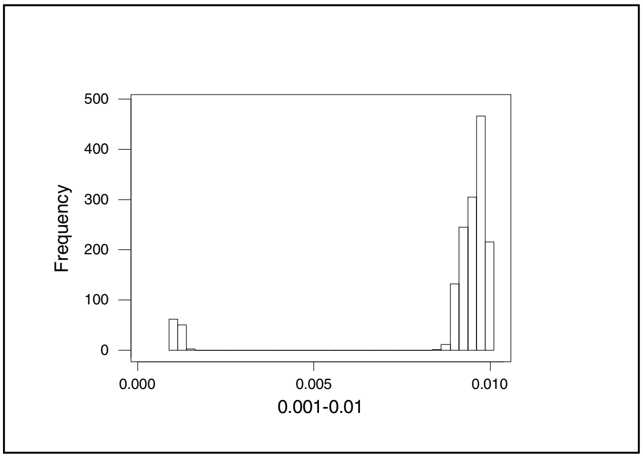

Figure 8: Histogram of Observed Data for VOIP Inter-Arrival Times

4.1 Overview of ODMRP

ODMRP is a multicast routing protocol that is optimized for mobile wireless networks where nodes move frequently and links have narrow bandwidth. Nodes that implement this protocol will behave as routers if they determine they are on the optimal path between an active sender and one or more of its receivers. To find this path, an ODMRP sender broadcasts Join Query packets whenever it does not have a valid route to one or more of the intended receivers. These Join Query packets are selectively broadcast through the network until they reach the receiver. The receiver chooses the Join Query packet that traveled along the optimal path, and uses that discovered path to build a Join Reply packet that is transmitted back to the original sender. A Join Reply packet contains the complete route from the sender to the receiver, and is used by all nodes on the route to set their forwarding flags and update their routing tables.

4.2 Modeling ODMRP in OPNET

OPNET has a very robust and flexible model of a wireless node, which consists of process models of the different layers of the network protocol stack. The challenge was to incorporate the ODMRP process into the existing node model while minimizing changes to the existing process models within it. Minimizing these changes to OpNet helped make the ODMRP model as portable as possible. The ODMRP process model was inserted between the transport and network layers, as shown in Figure 9, rather than at the network layer, because this approach eliminated the need for any changes to the existing IP process models, and required only small changes to the transport process model. The process models that are not part of the Mesh Radio were removed, most notably TCP (Transmission Control Protocol), since Land Warrior uses only UDP (User Datagram Protocol) datagrams.

The ODMRP model was developed as a state machine with four primary active states, as shown in Figure 10: Generating, Updating, Forwarding, and Responding. The Generating state is responsible for the creation and transmission of new Join Query packets to support the transport layer. The Updating state maintains the various caches and routes. The Forwarding state responds to packets that have not reached their destinations when the local node is set to forward them. Finally, the Responding state responds to Join Query packets by creating a Join Reply that incorporates the optimal path from the sender to the local node. Two additional states, Initializing and Idle, play a smaller role in the model. Initializing is responsible for registering ODMRP with the network layer, while the Idle state simply determines the nature of a packet and transitions to the appropriate state to handle it.

5 PRELIMINARY RESULTS

The first model of the Land Warrior system was a model of Land Warrior 0.6, which did not have the Mesh Radio. That model does not include the On-Demand Multicast Routing Protocol (ODMRP), which will be incorporated into the Land Warrior 1.0 system. This model concluded

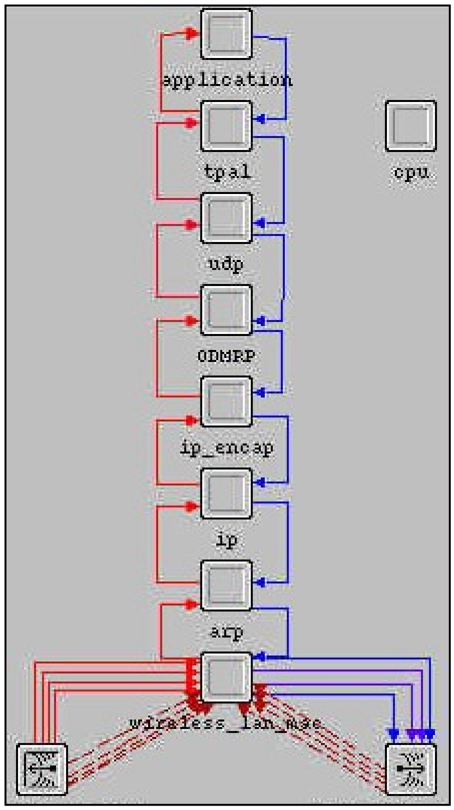

Figure 9: ODMRP Process Model Inserted into the Protocol Stack Between udp and ip_encap

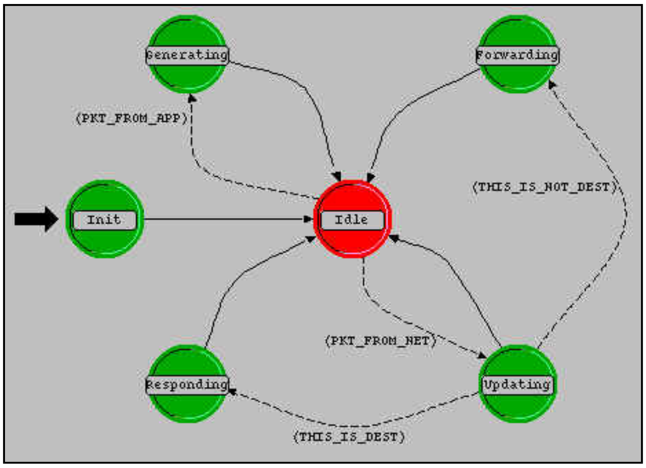

Figure 10: ODMRP Node Model

that at the platoon level, bandwidth is not a constraint. This result echoed what was determined experimentally at Fort Polk. When the model included the Mesh Radio, though no platoon-sized force has used the Mesh Radio in the field, the results were similar; Land Warrior communicates well at the platoon level.

6 FUTURE WORK

The first step in future work is to attempt to validate the platoon model. As no data exists on platoon that is equipped with the Mesh Radio, the current plan is to wait for the next platoon-level experiment and collect the needed data. With this data the input distributions and overall behavior of the system can be validated.

Part of the ODMRP route-search process will be stimulated by time; when the timeout threshold is reached, routes expire, and ODMRP begins the process of finding them again. Routes may also expire if a node attempts to use a previously-known route, but no response is received. To stimulate that part of ODMRP, an entity-level, Army constructive simulation will be used. A battle will be fought in the entity-level simulation, and the paths of the various entities will be recorded. These paths will be used to script the movement of Land Warrior nodes in OpNet. With the terrain and radio modules in OpNet, if line of sight is blocked between two nodes, the packets will not be received. Unacknowledged packets will stimulate ODMRP to attempt to discover a new route to the intended recipient.

Once the model is working properly with moving entities over terrain at the platoon level, larger forces must be simulated. The same process of scripting the movement of nodes in OpNet with information from a construction simulation will be used. The size of the force being simulated will be gradually increased to division level. The output of these simulation studies will be analyzed to predict the performance of the real system.

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