INTERDEPENDENCE OF TRAINING UTILITY AND NETWORK PERFORMANCE USING THE ARMSTRONG LABORATORY MULTISHIP RESEARCH AND DEVELOPMENT SYSTEM

Mr. Thomas L. Gehl, IBM Federal Systems Company; Captain Richard L. Rogers, AL/HRAE; Captain Mark A. Miller, AL/HRAD; Mr. Joseph Rakolta, Loral Defense Systems - Akron

ABSTRACT

To determine the value of a training system we must evaluate the system's design and performance with respect to the training effectiveness needed to support the operational mission. We will need a means to determine the relationship between a system's engineering design parameters and the training utility during a specified mission scenario. Through the research efforts of Armstrong Laboratory's Aircrew Training Research Division, we will address this need by using a networked multiship simulation system with experienced mission ready pilots, including Desert Storm veterans, flying specified mission scenarios. We will then relate network performance measurements to the evaluation of the training utility for critical segments of the mission scenarios.

We will also discuss the relationship between the training utility and network performance for specified mission scenarios. We will characterize the architectural components of the Multiship Research and Development (MultiRaD) training system and define the mission scenarios developed for the MultiRaD training utility evaluation. We will describe the test cases for measuring the network performance and present results of the network performance results with both average and worst-case segments of the mission scenarios. Finally, we will evaluate the network performance results with respect to the training utility and will recommend methods of extrapolating the results to future systems.

BIOGRAPHIES

Thomas L. Gehl is a lead system engineer for IBM Federal Systems Company Manassas research and development effort in system integration and networking core competencies. He is responsible for integrating and demonstrating real-time networked applications such as distributed interactive simulation. Mr. Gehl received his BS in Electrical Engineering and his MS in System Engineering from Virginia Polytechnic Institute and State University.

Captain Richard L. Rogers is Chief, Engineering Support Section, Aircrew Training Research Division, Armstrong Laboratory, Williams AFB, Arizona. He is responsible for the engineering support of advanced aircrew training systems and simulation research and development. Captain Rogers received a BS in Computer Science from the US Air Force Academy and a MS in Computer Engineering from the Air Force Institute of Technology.

Captain Mark A. Miller is Assistant Chief, Technology Development Branch, Aircrew Training Research Division, Armstrong Laboratory, Williams AFB, Arizona. He is responsible for managing the division's Multiship Research and Development program. Captain Miller received a BS in Engineering from the University of California, Los Angeles.

Mr. Joseph Rakolta is an Engineer with Loral Defense Systems - Akron, currently working at the Aircrew Training Research Division, Armstrong Laboratory, Williams, AFB, Arizona. His responsibilities include development and integration of networking hardware and software in support of the MultiRaD program. Mr. Rakolta holds a BS in Aerospace Engineering from the University of Cincinnati.

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RELATIONSHIP BETWEEN TRAINING UTILITY AND NETWORK PERFORMANCE

For this research effort, Armstrong Laboratory implemented a low-cost multiship simulation system as a training utility for offensive and defensive counterair mission scenarios. The network performance measurements occurred while teams of mission ready pilots flew specified mission scenarios in a realistic combat environment for a training utility evaluation.

As the missions were being performed, we measured the performance of the network system which provided the ability for the teams to play together in a simulated combat environment. To ensure unbiased results, we measured the network performance, independently, while the pilots flew their training sorties. The Training Requirements Utility Evaluation (TRUE), which was the training utility that the performance measurements were based on, was designed to determine the training potential of the MultiRaD system. Thus, we measured the network performance of the mission scenarios used to evaluate the training effectiveness of the system.

TRAINING SYSTEM ARCHITECTURE

Armstrong Laboratory designed the MultiShip Research and Development (MultiRaD) system to provide an environment that supports research into the effectiveness of using a network of simulators to provide aircrew training. The MultiRaD system integrates aircrew training simulators and an automated threat simulator over an asynchronous Ethernet Local Area Network (LAN) on which the SIMNET version 6.6.1 protocol with extensions communicates. The system consists of four aircraft simulators and their associated visual systems, a Ground Control Intercept (GCI), an Exercise Control Station (ECS), and an Automated Threat Engagement Simulator (ATES) interconnected over the Ethernet LAN as shown in Figure 1. For a more detailed description on the MultiRaD system see the paper titled "Development, Test and Evaluation of a Multiship Simulation System for Air Combat Training" by Captain Philip Platt and Dr. Peter Crane.

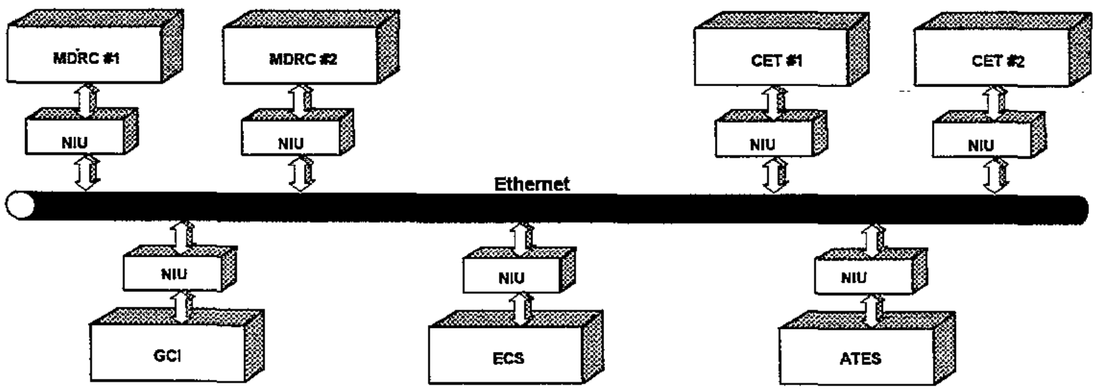

Figure 1. MultiRad System

Simulators

The manned flight simulators consist of two McDonnell Douglas Reconfigurable Cockpits (MDRCs) configured as F-15Cs and two Combat Engagement Trainers (CETs) configured as F-16Cs but visually represented on the network as SU-27s. The station simulates an AWACS controller station and provides intercept vectoring to the F-15Cs. The ATES provides various surface-to-air missile (SAM) threats as well as autonomous intelligent flight models (IFMs). The ECS collects and reproduces exercise data and provides an overview display of the gaming area to allow real-time control of the exercise. In the TRUE, Blue force consists of the two manned MDRCs and ATES provided Blue IFMs, and the Red force is made up of the two manned CETs and ATES provided surface-to-air missiles (SAMs) and Red IFMs.

Visual Systems

The visual systems for the aircraft simulators consist of a 24 ft. Full Field of View (FFOV) dome, a Display for Advanced Research and Technology (DART), a Mini-DART and a CRT. During this study, one MDRC used the FFOV dome which displayed four visual channels using a high resolution Area of Interest (AOI) headtracked over the complete dome and inset into lower resolution front, left and right channels. The other MDRC used the DART which displayed six visual channels on eight display screens, switching imagery from two of the front screens to two of the rear screens using headtracking. The CETs used the Mini DART, using only the front screen, and the CRT which provided only single channel displays. Even though the visual systems varied for each of the manned simulators, they were not evaluated in our analysis as to their effects on network or system performance. For an evaluation of the visual system effectiveness, see the paper titled "Visual Training Requirements for Networked Fighter Simulators, using Armstrong Laboratory's F-15 Training Requirements Utility Evaluation", by Captain Mark Miller.

Network Architecture

Each simulator communicates over the Ethernet LAN through a Network Interface Unit (NIU) which implements the SIMNET 6.6.1 protocol with Armstrong Laboratory extensions for air-to-air combat (i.e. SIMNET 6.6.1+). SIMNET 6.6.1+ defines the transport functions and the application information for the simulators to communicate. The transport functions are provided by the SIMNET Association protocol, and the application information is provided by the SIMNET Simulation protocol data units (PDUs) with extensions for RADAR and Emitter PDUs to support air-to-air combat. The MultiRaD simulators utilize the Activate Request, Activate Response, Deactivate Request, Vehicle Appearance, Fire and Impact PDUs from SIMNET 6.6.1 and the Radar, Emitter, and Freeze PDUs defined by Armstrong Laboratory to intitiate, control and communicate state information of the simulated world. In comparing the SIMNET PDUs to the Distributed Interactive Simulation (DIS) PDUs, the Vehicle Appearance is analogous to Entity State, and the Voice is analogous to the Signal PDU.

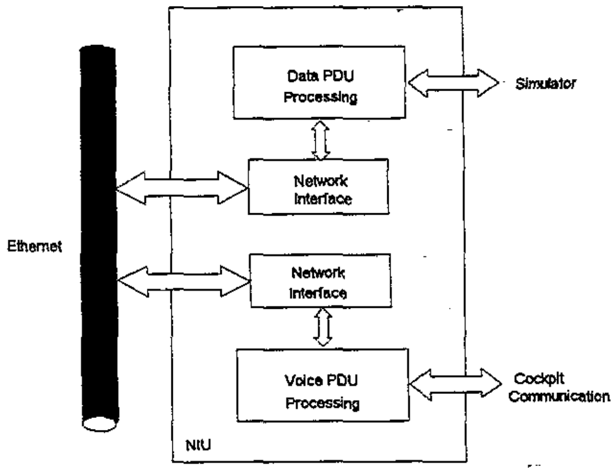

Figure 2. Network Interface Unit (NIU) Function Diagram

Implementing SIMNET 6.6.1+, the MultiRaD NIUs contain two Versa Module Europa (VME) 147 Central Processing Units (CPUs), one Ethernet card, one Simulated Voice, analog to digital (SIMVAD) card, and two VME 712 cards with a functional layout as shown in Figure 2. The two NIU CPUs run separate processes. The first 147 CPU interprets SIMNET 6.6.1+ network traffic via the Ethernet card, translates simulation information, and sends this information to a particular host simulator at a specified rate. The second 147 CPU processes and sends voice information between the network and the SIMVAD card. As an interface to the SIMVAD card, the 147 CPU processes and concatenates application information to the packetized voice from the SIMVAD card to create the voice PDUs. In the SIMNET NIU, the data and voice PDUs have separate processing paths for the translation and application-type processing.

In implementing the SIMNET protocols, the NIU translates and communicates simulation information between the distributed simulators. The NIU synchronously communicates to each host at a specified frame rate of 20 Hz for the MDRCs, 30 Hz for the CETs, 20 Hz for the ATES, and .1 Hz for the GCI, and asynchronously communicates the PDUs between the distributed hosts over the Ethernet LAN. To communicate between the distributed hosts on the network, the NIU uses group addresses with the multicast service to separate and filter voice and simulation PDUs on the network adapters to decrease the number of PDUs which must be processed by the NIU CPUs. Within each frame rate, the NIU services the host, services the network interface, performs dead reckoning on each entity, checks the thresholds on the host vehicle and passes information to the host. A more detailed description of NIU performance and functions is provided in the NIU Detailed Design Specification at Armstrong Laboratory.

To reduce the network traffic in communicating the Vehicle Appearance PDUs, we implemented dead reckoning or remote vehicle approximation (RVA) schemes in the NIUs. The dead reckoning algorithms extrapolate, linearly in time, the vehicle position based on the last velocity and time information received in the Vehicle Appearance PDU. To perform dead reckoning, the host calculates actual position along with the dead reckoned position and determines if the difference between the actual and dead reckoned positions exceeds a pre-defined threshold. If a threshold is exceeded, the host NIU communicates a Vehicle Appearance PDU to update the rest of the simulators involved. By communicating positional updates only when a threshold is exceeded, the dead reckoning algorithms significantly reduce the network traffic.

While it reduces the network traffic, the dead reckoning algorithms do not cause any apparent visual degradation. In our mission scenarios, the two MDRC simulators can fly formation with little to no jitter problems. For vehicles portrayed by the MDRC, CET and ATES simulators, the dead reckoning vehicle dimension thresholds corresponded to a length of 10m, a wing span of 20m, a vertical distance of 1m, and a rotation of 3 degrees. These lengths corresponded to a threshold of 10% of the actual vehicle dimensions. These vehicle thresholds in conjunction with the actions taken by the pilots on the particular simulators are to a large extent responsible for the frequency at which the Vehicle Appearance PDUs were communicated onto the network.

MISSION SCENARIOS

The mission scenarios for the TRUE represent those used in the Advanced Air Combat Simulation (AACS) at McDonnell Douglas. We intended to create situations where the two manned F-15Cs would meet aggressive threat aircraft and an integrated air defense system and make tough in-flight combat choices to perform their missions successfully.

The missions took place on the TACWAR data base, which is a Defense Mapping Agency (DMA) representation of western Washington state with an effective area of four degrees longitude by four degrees latitude. The designated Forward Edge of the Battle Area (FEBA) was 47 degrees North Latitude. In both the defensive and offensive counterair mission scenarios, the attacking team was based in the North and had an objective to strike the Chehalis Airfield in the South.

There were seven defensive counter-air (DCA) scenarios, and in all cases, the F-15 Combat Air Patrol started forty miles south of the FEBA, knowing that the threat axis was northerly. The objective was to defend the associated air defense lane, and all "high value" targets (i.e. Chehalis Airfield) from strike aircraft. Red aircraft were briefed as escorting SU-27 "Flanker" interceptors and radar jamming Mig-27 "Flogger" strikers. Additional risks in the mission included the possibility of chemical threat in the theater.

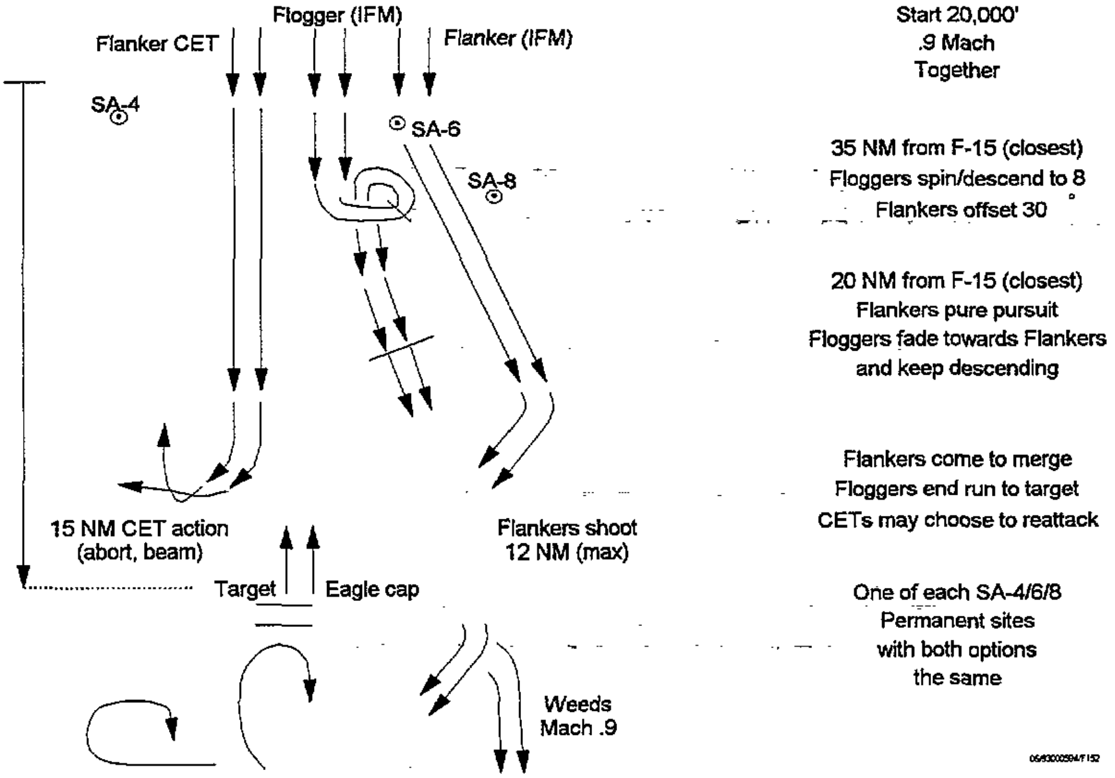

Figure 3. Defensive Counter-Air Champagne Tactic

Threat packages formed forty miles north of the border and ran a coordinated tactic, attempting to get the strikers through to the target. Fixed SAM sites, including the SA-4, SA-6, and SA-8 were situated north of the border within menacing range. Both sides considered a shooting war to be in progress and political borders were not a critical factor. Figure 3 depicts a "Champagne" tactic where Floggers spin to the low altitude block, while the escort attempts to mix it up with defending F-15 Eagle CAP in the south.

Two Flanker threats were provided by the CETs, and the other two Flankers as well as both Flogger aircraft were provided by the ATES. The F-15 pilots were not briefed on which aircraft were manned and which were unmanned or automated. Their challenge was to kill the Floggers north of Chehalis without falling prey to the escorts or SAMs.

In the six offensive counter-air (OCA) scenarios, the F-15s were tasked to escort four F-16s on a high priority bombing mission of Chehalis airfield from which Flanker Interceptors were operating in two-ship formations. The ingress route started 40 miles north of the FEBA and changed direction at the FEBA to head for the airfield. Figure 4 shows three Combat Air Patrols acting in defense of the red homeland. Of the six defenders, two were CETs and four were ATES entities. The four F-16s were also provided by the ATES as were three known SAM sites.

The OCA scenarios defined the maximum number of entities available for the TRUE. Initially, the OCAs required 10 ground threat sites with a mix of Anti-Aircraft Artillery and SAMs. During the integration, this number was dropped to three to enable the ATES to stay

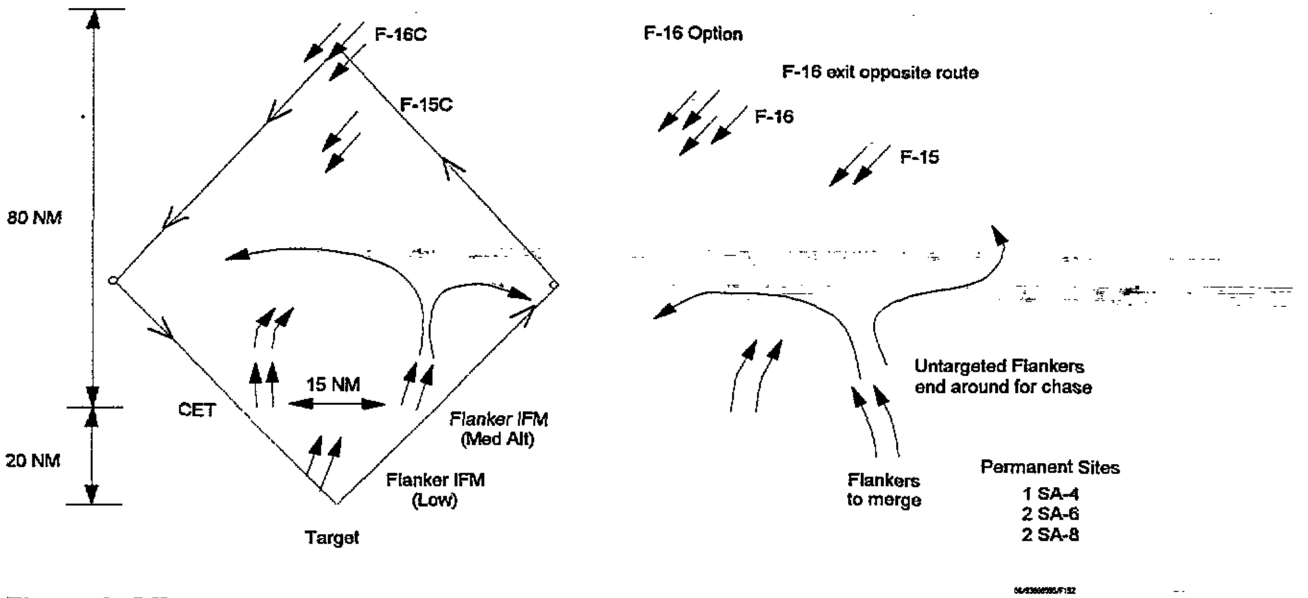

Figure 4. Offensive Counter-Air Maneuver

within the frame cycle of the simulation. In addition to the maneuvering during the engagements, both sides fired multiple missiles and the MDRCs dropped chaff and flares. We ensured that the systems stayed within their simulation frame rate while keeping the scenarios large enough to remain challenging.

TEST CASE AND RESULTS

We designed software tools on a SUN 3/80 and utilized a PC 386 Network Analyzer to measure the network performance during the TRUE studies conducted over several months. With the SUN 3/80, the network analyzer, and the data collection NIU, we captured a large quantity of network data that was available for post processing. For the purposes of determining results for this paper, we analyzed the data obtained during the last week of the TRUE study, when the system was most stable.

On the SUN 3/80 machine, we developed a software program to record network packet source Ethernet address, network packet length, SIMNET 6.6.1 packet type, and time of packet arrival to be used to determine the network performance during each simulation mission scenario. In conjunction, we monitored the network collisions, fragmented packets, misaligned packets, bad cyclic redundancy code (CRC) checks, and lost packets for each scenario, using the network analyzer to evaluate the degradation of the Ethernet performance. Finally, we modified an NIU to acquire NIU internal processing timing data.

PDU Rate and Bandwidth Distribution

For the results of this paper, we extracted information on network packet throughput and network bandwidth analysis representing forty-eight of the mission scenario that were conducted during the last week of the TRUE study. For each scenario, the first plot shows the number of kilobits that are transmitted across the MultiRaD SIMNET 6.6.1 network during each second, and the second plot corresponds to the number of network packets that were communicated across the MultiRaD SIMNET 6.6.1 network per second.

As the number of entities that participate in the mission scenario increases, the mean number of packets per second on the network, and therefore, the mean bandwidth of the network, increases proportionally. Also, the network traffic appears to be relatively constant over time with peak durations. With respect to the mission scenarios, those peak durations of packets communicated occurred during active engagements between the pilots and the entities participating in the mission scenario. These peak durations increase the network loading by approximately 2 to 3 times the normal packet rates of the mission scenario. Thus, by analyzing the PDU rate and bandwidth distributions over time for various mission scenarios, we are able to conclude that burst traffic produces approximately 2 to 3 times more network traffic than normal network loading for the offensive counter-air and defensive counter-air mission scenarios that were flown.

In evaluating the bandwidth required of the network for these mission scenarios, we measured an average bandwidth utilization of about 1 to 2.5% of the total available bandwidth of the 10 Mbps Ethernet LAN. We did not measure any Ethernet degradation for this low utilization, which is expected. Due to these network bandwidth results, we emphasized the analysis on packet throughput with respect to each device and PDU type.

Averaged PDU Rates

To analyze network performance with respect to individual simulators, we averaged the PDU rates of the mission scenarios for each device and each PDU type on the network. The four manned simulators - 2 F-15Cs (MDRC1&2) and 2 F-16Cs (CET1&2)--along with the ATES contributed practically all of the data PDUs for the respective mission scenarios. They also contributed almost all of the voice PDUs on the network; thus, contributing all of the measurable PDUs and bandwidth on the network for the respective scenarios. We evaluated the PDU types of Appearance, RADAR, Emitter, and Voice, explicitly, and grouped the Activate Request, Activate Response, Deactivate Request, Fire, Impact, and Freeze PDUs as Other PDUs. The Other PDUs contribute an insignificant amount over the mission scenarios. We analyzed the PDU rates of offensive counter-air and defensive counter-air mission scenarios of 2 Blue forces versus 4 Red forces (2 V 4), 2 Blue forces versus 6 Red forces (2 V 6), and 6 Blue forces versus 6 Red forces (6 V 6) with varying maneuvers. In these mission scenarios, the MDRCs participate as manned Blue forces (i.e. F-15Cs), the CETs participate as manned RED forces (i.e. SU-27s), and the ATES provides additional Blue and Red forces as IFMs. We averaged 5 missions for each engagement scenario (i.e. 2 V 4, 2 V 6, 6 V 6), to compare the differences between offensive and defensive counter-air network performance. (See Tables 1-4).

The manned vehicles contribute significantly more PDUs per entity represented than the unmanned. For manned Blue forces participating in offensive counter air missions, an average of about 17 PDUs per second are transmitted per entity of which about 75% are due to Vehicle Appearance PDUs and about 15% due to Voice PDUs. The manned Red forces transmit about 9 PDUs per second per entity represented with about 75% due to Vehicle Appearance PDUs and 15% due to Voice PDUs. Thus, the manned vehicles have the same distribution of PDUs types communicated, with the Blue forces communicating a larger total amount than the Red forces. This difference between the Blue and Red forces in the total number of PDUs communicated could be due to the fidelity of the vehicles being represented and the maneuvers that they are able to perform. In contrast, the unmanned simulator, ATES, transmits about 2 PDUs per second per entity represented with about 90% due to Vehicle Appearance PDUs and an insignificant percentage due to Voice PDUs (i.e. 1%). This significant reduction of PDUs per entity transmitted results from unmanned simulators using algorithms to control groups of entities with no tightly coupled human interaction to control the maneuvers of the specific entities while the manned simulators have tightly coupled human interaction per entity being represented.

For defensive counter-air, the manned Blue forces transmit about 13 PDUs per second per entity, with 70% due to Vehicle Appearance and 20% due to Voice PDUs. The manned Red forces transmit about 9 PDUs per second per entity, with 68% due to Vehicle Appearance PDUs and 25% due to Voice PDUs. The unmanned simulators transmit 2.5 PDUs per second per entity, represented, with 92% due to Vehicle Appearance PDUs and 1% due to Voice PDUs. The noticeable difference between the analysis of the offensive counter air and the defensive counter-air is the number of total PDUs per second transmitted by the Blue forces. This difference from 17 to 13 PDUs per second, 25% decrease, between the OCA and DCA for the Blue forces could be due to the difference in maneuvers required to perform the mission. For example, more vehicles (i.e. six Flankers instead of four Flankers), more shots, more chaff and more maneuvering requires more state updates; thus, contributing more PDUs.

PDUs/ ENTITY	TOTAL	APPEAR	% APPEAR	RADAR	EMITTER	OTHER	VOICE	% VOICE
TOTAL	73.6	50.2	68%	4.6	1.6	0.5	16.7	23
MDRC1	18.1	14.1	78%	1.5	0.2	0.1	2.1	12
MDRC2	16.8	11.7	70%	1.5	0.2	0.1	3.3	20
CET1	7.5	4.8	63%	0.8	0.2	0.0	1.8	24
CET2	9.5	8.0	84%	0.5	0.1	0.0	0.9	9
ATES	13.0	11.6	89%	0.3	0.9	0.1	0.1	1

Table 1: 6 V 6 (all offensive counter air) - standard deviation of total PDU rate=5.3

PDUs/ ENTITY	TOTAL	APPEAR	% APPEAR	RADAR	EMITTER	OTHER	VOICE	% VOICE
TOTAL	73.6	50.7	69%	5.2	1.9	0.2	15.6	21
MDRC1	17.1	12.8	75%	1.8	0.2	0.1	2.2	13
MDRC2	17.1	12.7	74%	1.4	0.2	0.1	2.7	16
CET1	4.9	2.9	58%	0.8	0.1	0.0	1.2	24
CET2	9.9	8.2	82%	0.9	0.2	0.0	0.6	7
ATES	15.9	14.1	89%	0.4	1.2	0.0	0.1	0

Table 2: 6 V 6 (all offensive counter air) - standard deviation of total PDU rate=2.7

PDUs/ ENTITY	TOTAL	APPEAR	% APPEAR	RADAR	EMITTER	OTHER	VOICE	% VOICE
TOTAL	42.2	24.9	59%	3.1	1.1	0.1	13.3	31%
MDRC1	13.1	8.5	65%	1.2	0.2	0.1	3.1	24%
MDRC2	10.7	6.9	64%	1.3	0.2	0.0	2.3	21%
CET1	2.2	1.7	76%	0.4	0.1	0.0	0.1	5%
CET2	0.1	0.1	100%	0.0	0.0	0.0	0.0	0%
ATES	8.5	7.7	91%	0.1	0.6	0.0	0.1	1%

Table 3: 2 V 4 (2 offensive and 3 defensive counter air) - standard deviation of total PDU rate=1.2

PDUs/ ENTITY	TOTAL	APPEAR	% APPEAR	RADAR	EMITTER	OTHER	VOICE	% VOICE
TOTAL	60.2	40.0	66%	3.9	1.3	0.3	14.7	24%
MDRC1	10.2	6.6	65%	1.1	0.2	0.0	2.3	22%
MDRC2	14.5	10.8	74%	1.6	0.2	0.1	1.9	13%
CET1	8.1	5.2	65%	0.6	0.2	0.0	2.0	25%
CET2	10.8	8.8	82%	0.6	0.2	0.0	1.2	11%
ATES	9.3	8.6	92%	0.0	0.6	0.0	0.1	1%

Table 4: 2 V 6 (all defensive counter air) - standard deviation of total PDU rate=2.3

The frequent occurrence of Appearance PDUs with an immeasurable number of Fire or Impact PDUs (i.e. event PDUs), emphasize that most of the PDUs communicated are due to the positional updates through the dead reckoning algorithms and not to voice and event occurrences. This conclusion can also be applied to the DIS PDUs since the Vehicle Appearance PDU is directly analogous to the Entity State PDU in the DIS standard.

For the mission scenarios performed, the total PDUs communicated over the network are distributed as 68% due to Vehicle Appearance, 24% due to Voice PDUs, 6% due to Radar PDUs, and 2% due to Emitter PDUs with the rest of the PDUs communicated very infrequently. The difference in the percentages of the total versus the individual simulators is due to the fact that the GCI and ECS transmit voice PDUs in controlling the exercises and the GCI also communicates some Radar PDUs as part of its functions. As the number of entities are increased, the percentage of PDU types will approach the percentages noted for the individual simulators since they will become more of a dominant factor over the quantity of PDUs needed for control functions.

CONCLUSIONS

For this study, we independently measured the network traffic of the TRUE while mission ready pilots flew their specified mission scenarios. Our study demonstrated relationships between the training utility and the network architecture which could be extrapolated for larger operational systems. Due to our preliminary results relative to the training utility, we recommend more direct analysis of pilot performance for specified aspects of the mission scenarios with respect to the network traffic. These more detailed studies should demonstrate further relationships between the *pilot performance, the mission scenarios, and* the network traffic.

In summary, we determined that approximately two-thirds to three-quarters of the PDUs communicated are due to Vehicle Appearance PDUs and that practically all of these PDUs were due to positional updates based on the thresholds set for the dead reckoning algorithms. This conclusion can be drawn since an immeasurable number of PDUs were communicated as Fire or Impact which would cause an event update, versus a positional update of the vehicles' appearances.

After analyzing the voice traffic, we concluded that voice PDUs provide 15-25% of the total network traffic when integrated over the same network as the data PDUs. This increase emphasizes that the predominant traffic is due to Vehicle Appearance, and not Voice PDUs, for highly interactive engagements. Also, we found that additional voice traffic can be caused by the controlling of the scenarios but that this additional traffic does not contribute significantly to the overall traffic on the network.

With respect to the training utilities, we found that the capabilities of the aircraft being simulated and the maneuvers required of those *aircraft affects the* PDU *rate transmitted by an* individual simulator. The more complex the maneuver causes more non-linear positional updates of the dead reckoning calculations which result in more Vehicle Appearance PDUs communicated to update the most accurate position of ownship. For example, we found that offensive counter air can cause approximately 25% more PDUs to be communicated than defensive counter air maneuvers, due to the increased maneuvering and events (i.e. shots and chaff).

Lastly, as expected, we concluded that unmanned vehicles only require about 2 to 3 PDUs *per second to communicate their state* changes which is less than manned simulators by a factor of 4 to 8, depending on the maneuvering fidelity performed. This makes sense since the unmanned vehicles are not driven by human interaction, which can be non-linear, and have many vehicles correlated in the algorithms that drive their maneuvers.

To further these conclusions, we recommend additional studies in the analysis of the *distributed interactive simulation environment* and supporting architectures. One aspect would be to analyze existing architectures in terms of their packet throughput capabilities with respect to the demands of the mission scenario. This study should be extended to gateways and routers, also, to determine the affects of such training over wide area networks. In performing these additional studies, techniques such as multicast and the relationship of group addresses to application information for the varying training utilities could be analyzed to determine the additional reduction of packet throughput.