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Interfacing Force-on-Force and Communications Models

MANA and JNE

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Preface

This report documents an interface between an agent-based force-on-force simulation and a high-resolution communication effects simulation. This report should be useful as a guide to users of the interface and assumes readers have familiarity with simulations and computer interfaces.

This research was sponsored by U.S. Army Training and Doctrine Command, Cyber Center of Excellence, Capability Development Integration Directorate, Cyber Battle Lab, and conducted within the RAND Arroyo Center's Forces and Logistics Program. RAND Arroyo Center, part of the RAND Corporation, is a federally funded research and development center sponsored by the United States Army.

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Summary

This report documents an interface between an agent-based force-on-force simulation and a network simulation for the U.S. Army's Cyber Center of Excellence, Capabilities Development and Integration Directorate (CDID), Cyber Battle Lab. One of the critical functions executed by the Battle Lab is to provide modeling and simulation (M&S) support to validate current and future command, control, communication, and network–related concepts, technologies, and architectures. It is charged with experimentation and assessment of advanced communications networks to support the tactical warfighter, live force play in exercises and demonstrations, supporting rapid integration and fielding of advanced command, control, communications, and computer technologies. They also provide direct support to the Ground Component Commander to enhance network and communications capabilities, among other demands. Given its predisposition to network support, the Battle Lab is in a unique position to stress existing M&S capabilities provided by the Army. The lab is exploring alternative M&S capabilities to add to their capability set, in particular the interface described in this report.

Specifically, this interface was designed to give the Army an additional capability, complementing existing M&S capabilities, to study the operational impact of current and future tactical networks. It also provides a quick-turn analysis capability to support experimentation and exercises facilitated by the Experimentation Division.

This report successfully interfaced the two simulation tools, an agent-based force-on-force simulation called the Map Aware Non-Uniform Automata (MANA) and a high-resolution communication simulation called the Joint Network Emulator (JNE). The Battle Lab uses JNE to examine the network's impact on missions. JNE simulates and near emulates radio systems such as the Joint Tactical Radio System (JTRS) and has been demonstrated at various network integration exercises. MANA's design differs from many of the force-on-force M&S tools the Army uses today. Examples include Joint Conflict and Tactical Simulation (JCATS), One Semi-Automated Force (OneSAF), and the Combined Arms Analysis Tool for the 21st Century (COMBAT XXI). Unlike MANA, these models

1. require a high level of physical detail
2. are predominated by deterministic entity behaviors and costly reactive behaviors.

These models have value for certain classes of research questions, but they struggle to address challenging problems, such as quantifying the operational impact of the network on the warfighter and mission outcome. This is primarily because studying the impact of the network depends greatly on reactive models of human (or autonomous) behavior—something for which traditional simulations are either not well suited because of their determinism or a high cost of

behavior development because of fidelity requirements. Networks are vehicles for information, and information has to be digested by entities that exist on the battlefield. This is the essence of John Boyd's Observe, Orient, Decide, Act (OODA) loop. Unfolding circumstances, outside information, and unfolding interaction with the environment are all aspects of observations that may influence an eventual action (Boyd, 1996). Those entities are presumably then able to make better-informed decisions: Move left instead of right, shoot instead of hold fire, or retreat instead of advance. When a model designer can predetermine the actions of entities in a simulation (as many of these models require to various degrees), he or she takes away the entities' decisionmaking capability, rendering useless any information that may change their decisions.

Many of these models also require detailed physics as part of their architecture. Some argue that this is often unnecessary (Galligan, Anderson, and Lauren, 2005) and very costly (Donaldson, 2014) and that it provides a false sense of realism. Donaldson's comments on COMBAT XXI are perhaps most damning:

> Developing the inputs for running a simulation in COMBAT XXI requires a significant investment in time and money. Building the input scenario for a recent Army study of a new ground combat vehicle (GCV) took nine trained analysts approximately seven months to complete. Even an entry level tutorial focused on a mechanized infantry platoon requires an estimated twelve hours to program.
>
> One of the reasons for such a long development time is that high-resolution simulations require entity behaviors to be programmed in a highly detailed manner. Additionally, these behaviors are often not reusable in other scenarios, or even by other entities in the same simulation (Donaldson, 2014, p. 2).

The Army is left in an obvious quandary. If the network is a vehicle for information, and information's primary purpose is to influence decisions, then why is it using models with limited (or excessively cumbersome) decisionmaking capacity to study the impact of the network? Furthermore, if many of today's analyses need answers quickly and in a budget-constrained environment, why is the Army using models that require huge investments in the form of time and dollars? A likely answer to both questions is *validity*. Army and U.S. Department of Defense (DoD) decisionmakers often want to know that an M&S tool is valid, and models that do not have high levels of physical rigor, and in which entities do not behave exactly as one would expect, are perceived to be less valid.

Adding further complexity to the problem, validity is highly subjective and difficult to demonstrate, by the Army's own admission:

> Validation involves the comparison of the M&S behavior and results to the data obtained from another credible domain. The credible domain is either believed to be the real-world, has been proven to closely approximate the real world, or is from a source that is recognized as expert on the relevant characteristics of the real world. . . . This is a critical part of the validation process because the real world is frequently not a tangible or empirically measurable entity, particularly in the realm of combat modeling (Headquarters, U.S. Department of the Army, 1999, p. 34).

The DoD Modeling and Simulation Coordination Office has noted similar challenges, specifically when dealing with human behavior representations (HBRs):

> All of the techniques applied to validating existing HBRs have significant limitations. As mentioned, testing domain correspondence requires unrealistic searches of very large and nonlinear behavior spaces. Testing psychological and physiological correspondences requires extensive validated models of psychological and physiological phenomena. While many comprehensive psychological models exist, relatively few of them have been applied to HBR validation, especially for simulation purposes (Modeling and Simulation Coordination Office, 2001, p. 20).

This presents a challenge. Army doctrine states that the real world is "frequently not a tangible or empirically measurable entity" but then paradoxically suggests that the leader of the validation effort must still define sources of information, concepts, and subject-matter experts (SMEs) to represent the real world. It further cautions that even if the validator finds usable historical data, if such data reflect outlier points, incorrect conclusions about the nature of the real world may result.

One can surmise that there are circumstances in which a SME can validate, generally, the structure and output of the M&S tool's approximation of the real world. Examples may include analyzing whether a soldier is capable of walking through a wall or whether a squad in the simulation appropriately avoids obstacles. However, this approach breaks down in more complex situations, with numerous entities making many decisions based on myriad inputs. It is impossible for a SME to analyze such complexity, hence the motivation for determinism to control the space of possibilities. Although this approach to identifying real-world behaviors and limitations makes some sense when the systems are known (e.g., a current weapon system) or when laboratory data, live-fire data, or historical data exist, it is inadequate for models that include humans. The only option that remains is a model based on scientific theory. In the end, for complex force-on-force models, validity remains a very subjective assessment.

Somewhere on the other side of the spectrum from high-fidelity force-on-force models is MANA. It was built based on two key ideas: that the behavior of entities is critical to exploring possible outcomes and that building excessively detailed models is a waste of time. According to MANA's developers,

> This is the essence of what we are trying to do: explore the greatest range of possible outcomes with the least set-up time. Since it is only necessary to have simple behavioural rules to achieve this, it seems almost pointless to make the rules more complicated than necessary (Galligan, Anderson, and Lauren, 2005, p. 34).

MANA is more challenging to validate (by today's Army doctrine) because it is capable of producing a wide range of potential outcomes, but it is precisely this outcome exploration that makes this type of probabilistic modeling well suited to network impact studies. MANA is designed in such a way that information generated within the model can be as fundamental to the behavior of entities as what is prescribed externally by a human coder. When scenarios are created that leverage this capability, they can provide a wealth of insightful observation. Unexpected things happen constantly in the real world, and models are arguably more valid when they consider that in their workings.

It is with this motivation that the Army has sought to explore MANA as a complementary tool to assist existing M&S options. MANA is capable of running in a stand-alone mode, but the objective of this report was to interface MANA with JNE. The Army wants to implement a force-on-force model that is sensitive to information in its high-fidelity network emulator that provides detailed representations of network and information propagation.

We completed four tasks for this report: (1) develop an application program interface for MANA, including customizing JNE's existing application program interface to interface with MANA; (2) enhance the capability of MANA so that it meets experimentation needs of the sponsor; (3) test and evaluate the enhancements to MANA and the interface in general; and (4) provide documentation, training, and support. This report, particularly Chapter Two, serves as the documentation of the interface.

The MANA-JNE interface was designed with performance in mind and is capable of running significantly faster than real time to maximize the number of scenarios it can explore. Further, the interface has been tested in concert with the Army's communication effects server, a large cluster capable of boosting simulation run times through parallelization. Test results can be found in Chapter Three of this report.

Finally, there are a number of actions the Battle Lab, the Cyber Center of Excellence, and the Army can take to advance this capability and others like it:

1. *Use the interface to support an operational impact analysis.* The interface gives rise to a modeling approach that is particularly well suited to quick-turn analyses because of the relative ease of designing scenarios. When the alternative is to use no modeling, or to leverage Excel spreadsheets, MANA may offer an insightful middle ground. To date, the interface has only been used as an exploratory tool for integration with other force-generation systems and demonstrated using an urban counterinsurgency mission.
2. *Explore alternatives to MANA.* For all of its benefits, there are limitations. The Cyber Center of Excellence may benefit from new approaches to M&S, such as a hybrid cognitive and agent-based model that focuses on information and security and draws from the strengths of MANA. It may draw on the strengths of the deterministic models by including parallel execution and improved terrain fidelity and by allowing for some manner of agent behavior scripting.
3. *Explore porting MANA (or similar agent-based models) to other types of network models*, such as the Navy Research Lab effort Extendable Mobile Ad-Hoc Network Emulator (EMANE) or NS-3. In doing so, the Cyber Center of Excellence could provide the Army with a robust M&S approach, complementing existing solutions while relieving it of a licensing contract. Two important objective areas are low-cost and fast operation.
4. *Revisit Regulation 5-11 and consider how validation can be achieved for different classes of M&S tools, such as agent-based.* The Army should also assess the validity of its M&S tools and determine whether its models are truly representative of a real world saturated with information. Revisit whether the Army has sufficient focus on reactive behaviors in its validation approach.

Chapter One of this report discusses the motivation for this research, M&S validity, and cost. Chapter Two introduces the structure and design of the MANA-JNE interface. Chapter Three provides details about the performance and verification testing for some basic tests scenarios. Finally, Chapter Four offers conclusions and recommendations to advance the Army's M&S capabilities.

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Abbreviations

API	application program interface
CDID	Capabilities Development and Integration Directorate
COMBAT XXI	The Combined Arms Analysis Tool for the 21st Century
DoD	U.S. Department of Defense
GUI	graphical user interface
HBR	human behavior representation
JCATS	Joint Conflict and Tactical Simulation
JNE	Joint Network Emulator
JTRS	Joint Tactical Radio System
MANA	Map Aware Non-Uniform Automata
M&S	modeling and simulation
OneSAF	One Semi-Automated Force
SA	situational awareness
SME	subject-matter expert
TTPs	Tactics, Techniques, and Procedures

CHAPTER ONE

Introduction

This report documents an interface between an agent-based force-on-force simulation and a network simulation for the U.S. Army's Cyber Center of Excellence Capabilities Development and Integration Directorate (CDID), Battle Laboratory Facility. One of the critical functions executed by the Battle Lab is to provide modeling and simulation (M&S) support to validate current and future command, control, communication, and network–related concepts, technologies, and architectures. Specifically, this interface was designed to give the Army an additional capability, complementing existing M&S capabilities, to study the operational impact of current and future tactical networks. It also provides a quick-turn analysis capability to support experimentation and exercises facilitated by the lab.

Motivation

Force-on-force M&S gives insight into military operations when other means are impractical for cost, complexity, or other reasons. The impact of the network on current and future forces is one such example of impracticality. There is a great variety of networking equipment, network settings, and architectures. Systematically exploring the possible combinations across a scenario space is impractical.

Further, studying the impact of a network depends on human (or autonomous) behavior because networks are simply vehicles for information, and information must be digested by entities that exist in the environment. This is the essence of U.S. Air Force Colonel John Boyd's Observe, Orient, Decide, Act loop. Unfolding circumstances, outside information, and unfolding interaction with environment are all aspects of observations that may influence an eventual action (Boyd, 1996). Those entities are then presumably able to make better-informed decisions: Move left instead of right, shoot instead of hold fire, or retreat instead of advance. It is for this reason, rich information interaction, that many of the force-on-force M&S tools used by the U.S. Department of Defense (DoD) struggle to address these challenging requirements. Some force-on-force models, such as Janus and Close Action Environment, have zero to limited reactive behavior modeling capability. Others, such as Joint Conflict and Tactical Simulation (JCATS), One Semi-Automated Force (OneSAF), and the Combined Arms Analysis Tool for the 21st Century (COMBAT XXI), have this capability but it often comes with great implementation and setup costs. An examination of the OneSAF version 8.5 operator manual indicates that, for many of the behaviors included with the model, there are no reactive behaviors programmed. At this stage of the model, the capability seems limited.

It is for these reasons that the Army is rightly interested in lower-cost models that still provide rich interaction. Therefore, this report explored and successfully interfaced the two simulation tools, an agent-based force-on-force simulation called the Map Aware Non-Uniform Automata (MANA) and a high-resolution communication simulation called the Joint Network Emulator (JNE). The Battle Lab uses JNE to examine the network's impact on missions. JNE simulates and near-emulates one or more Joint Tactical Radio System (JTRS)–based radios and has been demonstrated at various network integration exercises.

Unlike MANA, the Army's current M&S tools

1. require a high level of physical detail
2. are predominated by deterministic entity behaviors and costly reactive behaviors.[1]

Developers try to incorporate a high level of physical detail based on a belief that more detail will result in an M&S tool that is a better approximation of the real world. The reason for determinism is to ensure that forces play out a scenario as the modeler intends, usually with as much adherence to doctrinal tactics, techniques, and procedures (TTPs) as possible. In most cases, the entities in the model cannot make decisions on their own and require the modeler to tell them what to do; in others, they have some decisionmaking capacity, but it is limited and predefined because of the high cost of setup, particularly for large-scale engagements. They were not intended to consider the potential for diverse human behavior. While these models have value for certain classes of research questions, they struggle with such challenges as quantifying the operational impact of the network on the warfighter situational awareness (SA), action, and mission outcome. This is primarily because studying the impact of the network depends greatly on reactive models of human (or autonomous) behavior—something for which traditional models are not well suited because of their determinism. When a planner can predetermine the actions of entities in a simulation (as many of these models do to various degrees), he or she takes away the entities' decisionmaking capability, rendering useless any information that may change their decisions.

Therefore, we are left with an obvious problem. If a network is a vehicle for information, and information's primary purpose is to influence decisions, then why is the Army using models with little or no decisionmaking capacity to study the impact of its networks? A likely answer to this question is *validity*. Decisionmakers often want to know that the M&S tool is valid.

Modeling and Simulation Validity

Historically, validity has been derived from fidelity. Battlefield-entity decisionmaking was arguably less important when these models were developed because far less information was available to those entities than is the case today.

Presumably, this increased approximation of the real world and incorporation of TTPs is an attempt to satisfy DoD Instruction 5000.61 (U.S. Department of Defense, 2009), which established DoD policy that "models, simulations, and associated data used to support DoD processes, products, and decisions shall undergo verification and validation throughout their lifecycles" (U.S. Department of Defense, 2009, p. 2). The policy further notes that the same

[1] These models can incorporate probabilistic interactions for sensor detect, weapons hit, and other parameters. Some, such as OneSAF, include reactive behaviors, but its implementation of such behaviors are pre-planned, and therefore the potential for complex behavior interaction is much less than that of an agent-based tool such as MANA.

tools are to be accredited for an intended use. The Army complies with this policy in Army Regulation 5-11, *Management of Army Modeling and Simulation* (Headquarters, Department of the Army, 2014), and Army Pamphlet 5-11 implements the verification, validation, and accreditation guidelines (Headquarters, U.S. Department of the Army, 1999). The underlying presumption is that models that have been validated are more realistic. However, this report hypothesized that this presumption has at least two flaws:

1. Validating an M&S tool is difficult and costly.
2. Building models to meet stringent validation requirements tends to push them into a particular category of model: deterministic.

Army Pamphlet 5-11 defines validation as "the rigorous and structured process of determining the extent to which an M&S tool accurately represents the intended real world phenomena from the perspective of the intended use of the M&S" (Headquarters, U.S. Department of the Army, 1999, p. 30). It is unlikely that the intended use of the deterministic M&S tools is to explore the operational impact of a network, so we may question at the highest level whether a validation, as defined in DoD and Army doctrine, is useful. Further, according to that publication, there are two components to validation: a conceptual validation and an output validation. Regarding the conceptual validation of a simulation's internal workings, the pamphlet asks,

> Do the individual pieces (functional areas, weapon systems, units, behaviors and so forth) of the M&S adequately represent their counterparts in the real world? (Headquarters, U.S. Department of the Army, 1999, p. 32)

It is undoubtedly easier to represent the real-world performance of a weapon system than a human cognitive system. Adequate representation of behaviors is an enormous challenge. If M&S tools were capable of that, the world would already have robust, humanlike artificial-intelligence systems. In the interim, there are well-established and vetted theories that can be used to model human behavior. Though the applicability and correctness of such theories can always be questioned, a first step of validation can judge if the theories used are sound. Just because it is so difficult to capture behavior, modelers should not subsequently assume that soldiers will always act according to doctrine. There is also the question of how to model forces that have no overt doctrine, such as opposing forces.

The Army pamphlet further defines the validation process, a key part of which is the "identification of the real world," as follows:

> (1) Validation involves the comparison of the M&S behavior and results to the data obtained from another credible domain. The credible domain is either believed to be the real-world, has been proven to closely approximate the real world, or is from a source that is recognized as expert on the relevant characteristics of the real world. . . . This is a critical part of the validation process because the real world is frequently not a tangible or empirically measurable entity, particularly in the realm of combat modeling. The leader of the validation effort must define the specific sources of information, concepts, and SMEs [subject-matter experts] that will represent the real world and will be used as the baseline for both the structural and output comparisons. A description of some typical real world data sources follows.

a) *SMEs or other recognized individuals in the field of inquiry.* The process by which experts compare M&S structure and M&S output to their estimation of the real world is called face validation, peer review, or independent review.
b) Scientific theory and accepted algorithms defines the ranges of acceptable behavior in response to given inputs.
c) Laboratory test, developmental test, system operational test or other engineering data that provide a set of empirical data points, which correspond to specifically identified input data.
d) Training facility measurements and live fire training and tests results that may provide data points for comparison.
e) *Comparison with historical values.* Measurements of the phenomena of war, such as the number of casualties in a given battle, may provide only one or a small sample of relevant data points for comparison. Caution must be exercised if comparing the M&S to one historical data point because, if that one data point is an outlier rather than a norm, incorrect conclusions about the nature of the real world and the validity of the M&S may result. However, comparison with history, when combined with comparisons to other sources, forms a strong basis for credibility. (Headquarters, U.S. Department of the Army, 1999, p. 34)

The DoD Modeling and Simulation Coordination Office has noted similar challenges, specifically when dealing with human behavior representations (HBRs):

> All of the techniques applied to validating existing HBRs have significant limitations. As mentioned, testing domain correspondence requires unrealistic searches of very large and nonlinear behavior spaces. Testing psychological and physiological correspondences requires extensive validated models of psychological and physiological phenomena. While many comprehensive psychological models exist, relatively few of them have been applied to HBR validation, especially for simulation purposes. (Modeling and Simulation Coordination Office, 2001, p. 20)

Army doctrine seems to present an interesting paradox. It states that the real world is frequently not a tangible or empirically measurable entity, but then it suggests that the leader of the validation effort must define sources of information, concepts, and SMEs to represent the real world. It further highlights that, when comparing to historical data, if such data reflect outlier points, incorrect conclusions about the nature of the real world may result.

One can surmise that there are circumstances in which a SME can validate, generally, the structure and output of the M&S tool's approximation of the real world. Examples may include analyzing whether a soldier is capable of walking through a wall or whether a squad in the simulation appropriately avoids obstacles. This is akin to the output validation referred to by the pamphlet.

> Does the M&S produce results that are feasible?
>
> How does the M&S output compare to historical data, test data, laboratory data or exercise data?
>
> Are graphical outputs and visualization realistic? (Headquarters, U.S. Department of the Army, 1999, p. 32)

However, this approach breaks down in more complex situations with numerous entities making numerous decisions based on numerous inputs. It is impossible for a SME to analyze such complexity, hence the need for determinism to control the space of possibilities. Although this approach to identifying real-world behaviors and limitations makes some sense when the systems are known (e.g., a current weapon system) or when laboratory data, live-fire data, or historical data exist, it is not adequate for models that include humans. The only option that remains is a model based on scientific theory. In the end, for complex force-on-force models, validity remains a very subjective assessment.

Modeling and Simulation Cost

Even if one assumes that the current approach does determine some level of validity, the question of exploring scenarios that incorporate human behavior remains. Seemingly small choices can have large cumulative effects in combat. If a deterministic M&S tool is programmed to explore a range of possible outcomes (related to behavior, not just probability of detection or casualty), it must script each outcome in some capacity, and each script incurs some cost. A 2014 Naval Postgraduate School study using COMBAT XXI noted just that:

> Developing the inputs for running a simulation in COMBATXXI requires a significant investment in time and money. Building the input scenario for a recent Army study of a new ground combat vehicle (GCV) took nine trained analysts approximately seven months to complete. Even an entry level tutorial focused on a mechanized infantry platoon requires an estimated twelve hours to program.
>
> One of the reasons for such a long development time is that high-resolution simulations require entity behaviors to be programmed in a highly detailed manner. Additionally, these behaviors are often not reusable in other scenarios, or even by other entities in the same simulation. (Donaldson, 2014, p. 2)

Furthermore, simply working with high-resolution models is costly. A recent ALATEC Corporation press release reported that the company won a task order to "construct a dynamic force-on-force combat situation using the Scenario Integration Tool Suite (SITS) and the COMBAT XXI model" (ALATEC, 2014). The contract increases the model's level of effort to 33 personnel. COMBAT XXI is not alone. A search for OneSAF contracts shows that no less than $88 million has been awarded since 2007 (USASpending.gov, 2015).

These models have great utility in areas in which behavior is not a great consideration, such as comparing the performance of weapon systems. They may even be useful in exploratory research in which behavior *is* a consideration, but this is likely to come at a considerable cost.

Assumptions About Communications

One final motivational question concerns assumptions about communication. Despite their rigor from a physics standpoint, many of these models have historically made assumptions about communication. Communication can be so demanding that those models that can, such as OneSAF, use a communication effects server, such as JNE, to provide communication modeling.

Map Aware Non-Uniform Automata (MANA) Use

In its approach to operational impact modeling, the RAND Corporation has been using an M&S tool developed by the New Zealand Defence Technology Agency called Map Aware Non-Uniform Automata (MANA). The agency has extended to RAND and the Army permission to use the MANA model. MANA is an agent-based model, a particular class of models in which entities (called *agents*) have simple rules defining their behavior. MANA builds on models developed by the Center for Naval Analyses and the U.S. Marine Corps, namely by Andrew Ilachinski, in the late 1990s. In some cases, agent-based models can be used as a substitute for traditional deterministic combat models, as a precursor to trimming down scenario possibilities or, side-by-side, as a separate line of effort. In agent-based models, the physics of the world are generally more abstract than in the models discussed earlier.

The primary catalyst for the New Zealand Defence Technology Agency to develop MANA was a frustration with the limited ability to explore SA, command and control, and the information domain. The agency describes the deception of detailed models in the MANA version 3 manual:

> [T]o rely on models built "on a bedrock of physics" is to deceive ourselves. It is a myth that a more detailed model is necessarily a better model, because it is impossible to capture accurately every aspect of nature. In fact, the more detailed a model is, the more obscure its workings, a problem that is compounded if the user is not the model designer. (Galligan, Anderson, and Lauren, 2005)

Therefore, the researchers built MANA based on two key ideas: that the behavior of entities is critical to exploring possible outcomes and that building excessively detailed models is a waste of time. The manual's authors go on to note,

> This is the essence of what we are trying to do: explore the greatest range of possible outcomes with the least set-up time. Since it is only necessary to have simple behavioural rules to achieve this, it seems almost pointless to make the rules more complicated than necessary. (Galligan, Anderson, and Lauren, 2005)

Perhaps most importantly, they added a capability to model communication using SA contacts as the primary type of data that gets transmitted. In 2006, RAND studied a number of scenarios using this capability and identified three key parameters of networking capability that affect warfighter effectiveness: sensing, communication, and cognitive (Porche and Wilson, 2006).

That RAND study leveraged work by Porche, Jamison, and Herbert (2004), which used a high-resolution network model called QualNet, developed by Scalable Network Technologies, to build a dynamic meta-model of communication reliability based on traffic load. The resulting meta-model was incorporated into MANA and studied by Porche and Wilson (2006). In 2004, Porche, Jamison, and Herbert had speculated on the utility of directly interfacing MANA and QualNet in real time; Wilson and Porche briefed the completed work at the 2005 International Command and Control Research and Technology Symposium, in a briefing titled "Integrating High-Resolution Network Simulation with Force on Force Combat Models: Connecting MANA and Qualnet" (Wilson and Porche, 2005). The core of the original interface was updated and modernized in the current report to connect MANA to JNE, a simulation based on QualNet.

Motivation Summary

In summary, behaviors are an important M&S consideration when trying to understand complex phenomena, such as the operational impact of the network on the warfighter. Determinism and the high cost of high-fidelity reactive behaviors limit the possibilities for humans (or automatons) to make behavior-based decisions in complex scenarios. Additionally, high levels of physical rigor are often unnecessary, can be very costly, and provide a false sense of realism. Many models leverage determinism and detailed physics in an effort to make them seem more valid. Yet, validity is ultimately highly subjective and difficult to confirm, by the Army's own admissions in doctrine.

Detailed models will provide insights, but it is misleading to purport that they are valid for a range of questions the Army is interested in addressing. They may be valid only for their intended purpose, which is not necessarily to study the operational impact of networks. They ultimately produce data that have at least a few assumptions:

- The scenario under exploration will play out as scripted.
- Entities will act according to doctrine at all times.
- Nothing unexpected will happen.

This makes reasonable sense. The military writes doctrine with the intent that it be followed, and it trains to that doctrine. The same should be expected of the military's M&S tools. Decisionmakers want to base their decisions on information and analysis that have these underpinnings.

However, this approach also has problems. For example,

- The results depend greatly on the quality of the scenario's script, and complex scenarios can become very costly in time and money to develop.
- Soldiers do not always follow doctrine and are always making choices on the battlefield.
- Unexpected things happen constantly in the real world.
- More detailed models do not always produce realistic results.

Of course, the real world is far more complicated.

Study Tasks

Our research consisted of four tasks: (1) develop an application program interface for MANA, including customizing JNE's existing application program interface (API) to interface with MANA; (2) enhance the capability of MANA so that it meets the experimentation needs of the sponsor; (3) test and evaluate the enhancements to MANA and the interface in general; and (4) provide documentation, training, and support. The tasks were described as follows:

- *Task 1: Develop an API for the MANA model, an agent based, force-on-force model, to interface with the JNE communication model.* We will develop the API to interface MANA and JNE interactively. The code and documentation for the use of the API will be provided to the sponsor. We will leverage the API developed for MANA version 4 and the add-on code developed to interact with QualNet. The team will also explore the utility of migrating the MANA version 4 API to MANA's current version 5 and recommend a path forward for the Battle Lab in its use of MANA.
- *Task 2: Enhance the capability of the agent-based tool so that it meets the experimentation needs of the sponsor.* MANA source code (for version 4 or 5, according to the preference of the sponsor as determined by task 1) will be modified, tested, and recompiled with new features that are essential for experimentation plans. This may include enhancing existing human behavior in the loop interaction with force-on-force agents that are modeled.[2]
- *Task 3: Test and evaluate the enhancements to MANA that were added in task 2.* We will test the enhancements to MANA with sponsor-provided scenarios and vignettes in a manner that demonstrates the usability of the interfaced tools and functionality of the MANA-JNE pairing.
- *Task 4: Provide documentation, training, and support.* We will provide a user's guide for the MANA API developed in task 1, as well as the new MANA functionality provided in task 2. In addition, the test scheme developed for task 3 and the evaluation results will be documented in a report. We will provide assistance to Battle Lab personnel as needed in their implementation of the API into its test bed and provide software support to Battle Lab users as needed during this project's period of performance.

This report, particularly Chapter Two, serves as the documentation of the interface.

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2 In retrospect, this task would have been better worded as enhancing the tool to meet a relevant subset of requirements for the sponsor. Experimentation needs are broad and constantly changing and it would be very difficult to meet all of those needs with one tool.

CHAPTER TWO

The Interface

The Army Cyber Center of Excellence, CDID, Cyber Battle Lab is charged with experimenting and assessing advanced communications networks to support the tactical warfighter, live force play in exercises, and demonstrations and supporting rapid integration and fielding of advanced command, control, communications, and computer technologies. It also provides direct support to the Ground Component Commander to enhance network and communications capabilities, among other demands. Given their predisposition to network modeling, the Battle Lab is uniquely positioned to stress existing M&S capabilities provided by the Army. Given the motivations discussed, the lab is exploring alternative M&S capabilities to add to their capability set. The lab currently uses a model called *JNE* to support their network modeling objectives, and JNE acts as their primary network model that interfaces with force-on-force simulation.

The interface developed as a part of this report acts as a bridge between MANA and JNE and also between an abstract force-on-force model and a more-detailed network model.

The objective of this effort was to leverage previous RAND work to interface MANA with QualNet and create an API for MANA and JNE. The resulting interface should provide the Battle Lab with a low-cost, quick-turn exploratory operational effectiveness analysis capability.

We used the latest available version of MANA (version 5) to connect to the latest version of JNE (version 4.4). This report assumes a reader has some knowledge of setting up MANA and JNE scenarios. For more information on the capabilities of various versions of MANA, the Naval Postgraduate School's International Data Farming Workshops are a good reference (McIntosh et al., 2007). More information about JNE can be found at the Scalable Network Technologies website (Scalable Network Technologies, 2014).

Interface Concepts

The current implementation of the interface features a custom Indy socket on the MANA side and connects to a JNE external interface model in JNE.[1] During a time step in MANA, the interface uses different types of packets to communicate:

- movement packets that contain information about the agent that is moving; its x, y, and z coordinates; a theta to describe orientation; and the agent's status

[1] Indy.Sockets is an open-source client/communication library.

- message packets that contain information about source and destination, link number, and size of the payload, as well as confirmation of message receipt in JNE
- timing packets that help synchronize the two simulations.

Figure 2.1 shows the interface communication.

Output Packet Structure

MANA sends messages in the following order:

- movement packet
- message packet
- end-of-step packet.

Each is preceded by a packet header with information about the type of message and its size. The first thing the user receives is a packet header for the movement of agents.

Packet Header

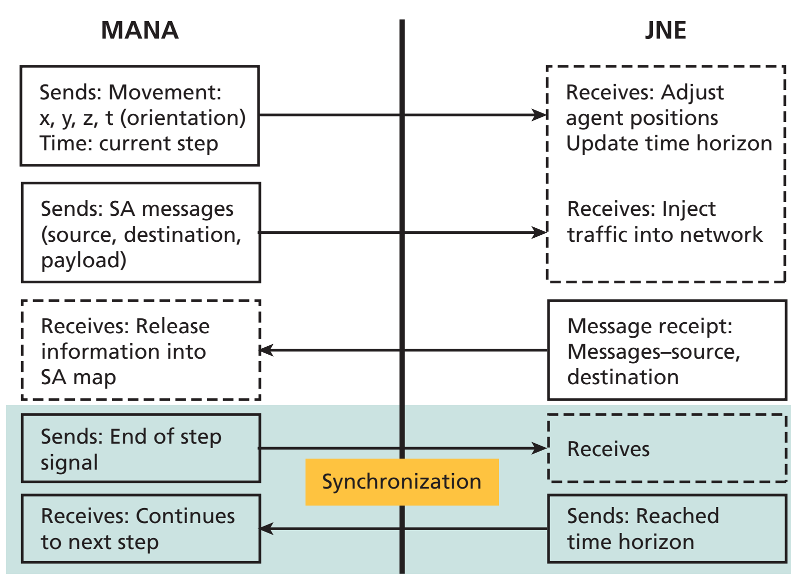
The packet header is 8 bytes with two integer fields, as described in Table 2.1.

A command of *1* is a movement update, *2* is a message update, and *3* is an end-of-step update.

Movement Packet

After the movement header, the user can expect to get a movement packet for the number of squads (squad radios) or number of agents (agent radios) for the blue force in the simulation. The number of updates is calculated by multiplying the packet-header data-length value by the size of the movement packet (44 bytes), as described in Table 2.2.

Figure 2.1
The Interface Design



RAND *TL201-2.1*

Table 2.1
Packet Header Composition

Variable : Type	Comment
Command : Integer	Identify to JNE what type of packet to expect
Data length : Integer	The number of movement packets to expect

Message Packet

The message packet is 26 bytes. Similar to the movement packet, the user should expect to first see a header with the command 2, followed by a number of message packets specified by data length, as shown in Table 2.3.

It is important to note that, when MANA initializes the interface for a remote tool, it creates a new list of units that correspond to the radios being modeled in that tool. So, if a JNE source or destination squad is not enabled or is not blue-allied, it will be skipped in this list. The source and destination ID will be from this list, not the squad number or agent number in MANA. The actual MANA squad number can be found in the movement packet.

Table 2.2
Movement Packet Composition

Variable : Type	Comment
Agent counter: Integer	Total number of agents
Current step: Integer	Current time step
JNE ID: Integer	The JNE ID (of the agent or squad)
Squad index: Integer	The index of the squad
x: Double	*x* coordinate (or decimal in geodetic)
y: Double	*y* coordinate (or decimal in geodetic)
z: Integer	z coordinate (height)
Theta: Integer	Agent orientation (0–360 degrees)
Status: Integer	Current agent status: 1 = active, 2 = dead, 3 = injured, 4 = unknown

Table 2.3
Message Transmit Packet Composition

Variable : Type	Comment
Source: Integer	JNE specific source squad
Destination: Integer	JNE specific destination squad
Size: Integer	Message size (in bytes)
ID: Integer	Unique message ID
Link number: Integer	MANA link number
Source index: Integer	MANA source squad index number
Agent index: Small Integer	MANA source agent index number

The link number and source index are important for the return packet, but they may also be useful to the remote modeling.

Return Packet Structure

MANA is effectively always listening for return packets, but it processes the packets only after it has sent movement, message, and end-of-step messages. The return messages can be sent back at any time, but MANA will cease processing them for a given time step once JNE signals that it has reached the time horizon. The return packet structure is the same as the transmitted structure.

End-of-Step Packet

The end-of-MANA-step packet signals that MANA is done sending messages for this step and is now waiting for JNE to signal that it has completed the time step as well. This is referred to as the simulation horizon in JNE. The end-of-step packet is only a packet header and sends a command 1 to signal that JNE has reached the horizon.

Setting Up the Interface in MANA

Within each time step, MANA attempts to execute a set of tasks for its list of squads and their subordinate agents. The interface adds hooks at certain key points of that loop to capture position and SA information and send it to JNE. The interface has been designed so that MANA controls JNE. It can be run with MANA in its graphical user interface (GUI) mode or in command-line mode. Within the MANA GUI, a user can set various interface settings:

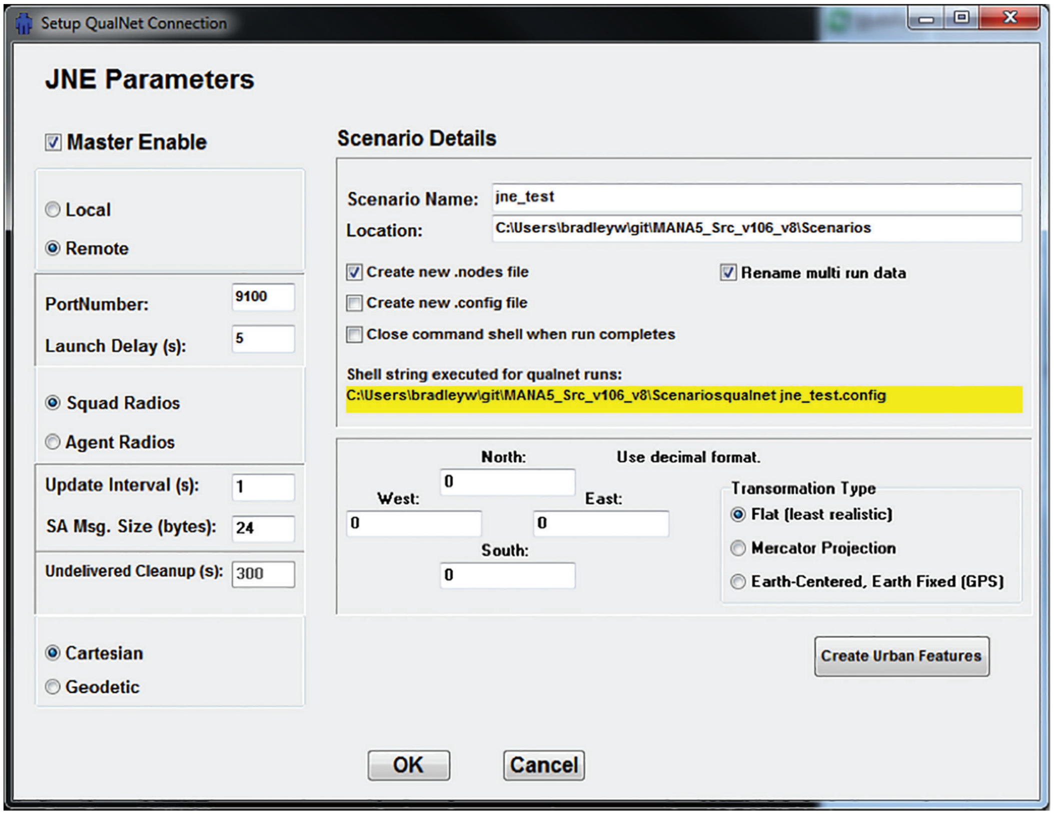
- master enable, a switch to turn the interface on or off. If it is unchecked, it is off, and MANA will use its intrinsic communication models
- local/remote, the location of JNE (local is on the same machine as MANA)
- port number, the port number to use for a local or remote socket session
- launch delay, how long MANA waits before it launches a local JNE session (this is useful for allowing the sockets to reset)
- squad/agent radios, how to apply radios into MANA agent constructs
- update interval, how often MANA sends communications updates to JNE
- SA message size, the size of an SA message to be modeled in JNE
- undelivered cleanup, the time to wait before cleaning up memory of undelivered messages in MANA
- cartesian/geodetic, the map coordinate system, along with its corresponding map setup parameters: flat, mercator, and earth-centered, earth-fixed
- scenario details parameters are also available and based on the location path template JNE nodes and configuration files can be created.

Figure 2.2 shows a screen shot of the scenario parameters GUI.

Squad and Agent Radio Concept

MANA squad and communications are important concepts in the interface. MANA has "squads," which are groups of agents that share the same personality characteristics. Squads can consist of any number of agents (with no relation to the U.S. Army doctrinal defini-

Figure 2.2
Scenario Parameters GUI in MANA



RAND *TL201-2.2*

tion of a squad). MANA squads share SA intrinsically. Communications occur on "links" between squads, sharing inorganic SA. Once a message is delivered to a squad, the message is instantaneously shared among its members. These communication links are interrupted in the MANA-JNE interface and modeled by JNE.

When using the squad radio setting, each squad in MANA has only one radio that is modeled in JNE. Figure 2.3 shows this setup for a seven-agent squad in MANA.

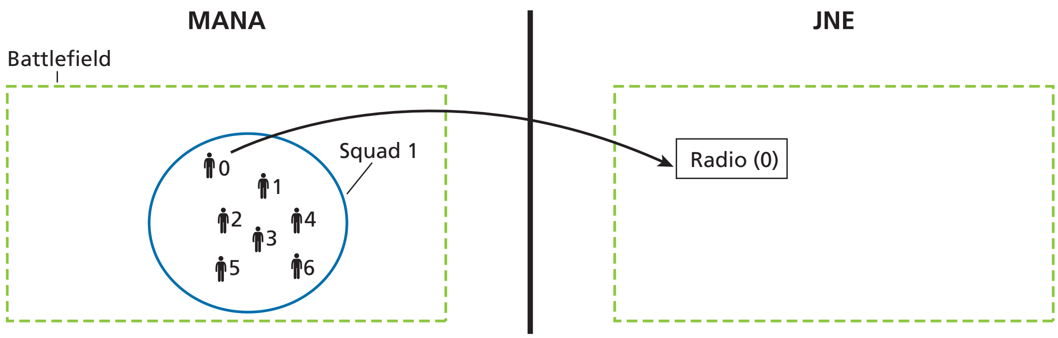
When using the agent radio setting, each agent has a radio in JNE. This is shown in Figure 2.4 for a MANA squad with three agents.

The current version of MANA was not designed to function in a situation in which each agent has a communication capability. Therefore, in agent radio mode, any agent may transmit a message, but that message is always transmitted to the first member of the receiving squad. After that, it is disseminated to the rest of the squad.

Modifying the JNE Interface

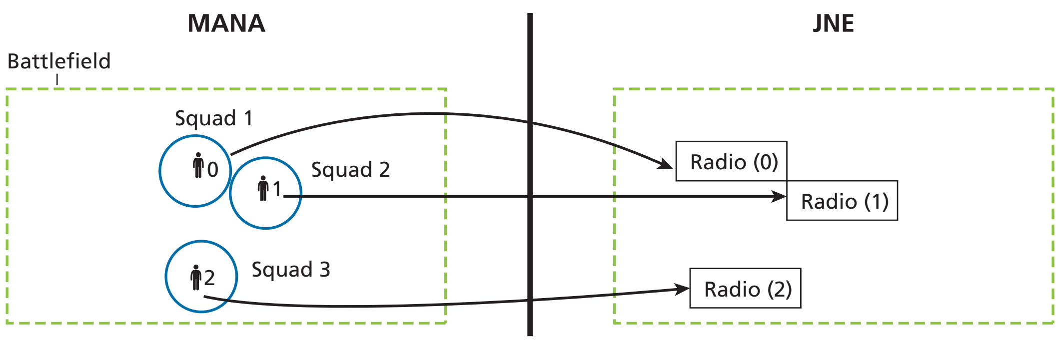
There are two JNE files that have been altered to enable JNE interface with MANA: *external.h* and *external.cpp*. Table 2.4 describes these files.

Figure 2.3
Squad Radio Concept



RAND *TL201-2.3*

Figure 2.4
Agent Radio Concept



RAND *TL201-2.4*

Callback Functions

In a nonparallel environment, JNE registers each callback function only once. However, in a parallel environment, JNE will register a callback for each partition if allowed. Therefore, the important architectural decision to note is that four of the MANA callback functions are limited to only the base partition (presumably partition 0). These are MANA_Initialize, MANA_ReceiveMessages, MANA_Time, and MANA_SimulationHorizon. MANA_Initialize is where the socket connection to MANA is created, and this should be done only

Table 2.4
Preexisting JNE Files Altered

Filename	Comment
/jne/4.4/include/external.h	Added EXTERNAL_MANA to the ExternalInterfaceType enum, and increased the EXTERNAL_TYPE_MAX to 128. Add the change ahead of the EXTERNAL_TYPE_COUNT field. This change is required so that other partitions (in a parallel execution) can send data back to the MANA interface, which runs only on the base partition 0.
/jne/4.4/main/external.cpp	This is the primary location where the user adds a new external interface, and MANA is no exception. JNE is alerted to MANA's existence in this file, and MANA's callback functions are registered. ADDON_MANA is used to define MANA to JNE. Each callback function is prefixed with "MANA_".

once. MANA_ReceiveMessages is called to check the socket for information from MANA. MANA_Time and MANA_SimulationHorizon keep track of time in MANA and the time horizon for JNE, both areas in which, for now, only one instance is required. The interface has not been designed to perform any of these functions in parallel.

The remaining external interface callback functions will be created for each partition in a parallel environment. These are MANA_SendMessages, MANA_InitializeNodes, and MANA_Finalize. MANA_SendMessages sends information about messages received at their destination in the JNE network. Within mana.cpp, MANA_SendMessages checks whether the current partition is partition 0; if it is not, it calls EXTERNAL_RemoteForwardData, which forwards the message delivery to partition 0 for transmission back to MANA. This is necessary because additional partitions (other than partition 0) do not have a pointer to the socket. MANA_InitializeNodes initializes nodes on the local partition and creates local variables to store their information, such as the agent_info array. MANA_Finalize closes and cleans up the socket—useful in a multiple-run environment.

Conducting a Run

As JNE is a network model, a representation of a network to be simulated is required. This is often a tactical radio network, but could also include satellite or wired communications. A joint run of the two models need not be complex. A user can test the interface with as little as two radio specifications in JNE and two squads in MANA, each with one agent each, and an inorganic communications link setup between the two squads.

The procedure in GUI mode for conducting a combined run of the two models is as follows:

1. Launch MANA and open the scenario. Note that the external interface will create SA messages only for squads with inorganic communication links, logical links to be able to share SA. There are movement messages for all squads or agents (depending on the selection parameters), regardless of whether they have inorganic links.
2. Set up the JNE interface parameters. “Local” is a deprecated option for the older version of QualNet that could run inside Microsoft Windows. With “Remote” selected, MANA will wait for JNE to start a socket handshake. To conduct a batch run, a script needs to be executed on JNE to initiate the socket connection to MANA.
3. Click the “Run” button.
4. Once running, MANA expects all message completion data to come from the external source. No SA messages will be released onto SA maps without a message confirming it. Note: All MANA communication parameters will be ignored. Both simulations should self-terminate at the conclusion of the run.

Challenges

There were a number of challenges to interfacing these two disparate models. A short list includes:

- Synchronizing a discrete event simulation such as JNE with a step-loop simulation such as MANA. Among other concerns, it requires alignment between the abstract time interval in MANA and its counterpart in JNE. This was overcome by managing communication between the two models very closely in Indy sockets and allowing each model to do as much as it can while minimizing synchronization wait. JNE's simulation horizon parameter setting is particularly helpful in this endeavor.
- During a multi-run analysis, it is important to ensure that MANA can remotely launch and close JNE. This is especially challenging, as MANA is native to Windows and JNE to Linux. The interface development effort posits a dynamically generated shell script to manage JNE. All testing and experimentation manually launched JNE after manually launching MANA. The CDID is exploring automation through the dynamic shell script.
- Managing multiple levels of communication that are internal to MANA. MANA has a concept called *squad communications*, where squads are able to share SA contacts organically, as if they were connected. Turning off intra-squad communications in MANA also shuts off the inter-squad communications the MANA-JNE uses. Therefore, it is important for model developers to consider intra-squad in scenario construction and likely minimize the size of MANA squads.

CHAPTER THREE

Test Results

Test Scenarios

We created five basic test scenarios to explore the interface. These tests were designed to explore simulation performance times as the number of agents increased. Test 1 is considered the most basic test possible of the interface, as it includes two blue agents, each in their own squad, communicating with each other. There is only one target agent in the scenario. The scenarios increase the number of agents to explore robustness, in terms of the interface's ability to handle large amounts of data without crashing, and also speed of execution. Additional scenarios should be developed to explore military radio systems, terrain, and long-duration runs. Table 3.1 details the test scenarios.

Performance Tests

We conducted several performance tests to explore the robustness of the interface. The test environment consisted of a desktop computer running JNE in single-CPU mode, and a mobile laptop running MANA. Table 3.2 shows the parameters for these tests.

Further tests should be conducted using the communication effects server, particularly for scenarios 4 and 5. The interface did not experience any anomalies during the large-scale tests and is thus deemed reasonably robust to errors during high-intensity runs. However, the tests indicate that when more than 200 agents are used, more than a laptop and a desktop computer are required for increased analysis performance.

Table 3.1
List of Test Scenarios

Scenario Name	Number of Blue Agents	Number of Blue "Squads"	Number of Red Agents	Duration (Seconds)	Terrain (Square Kilometers)	Physical Model	Network
jne_test_1	2	2	1	500	None	802.11b	1 subnet
jne_test_2	3	2	1	500	None	802.11b	1 subnet
jne_test_3	100	2	100	500	None	802.11b	1 subnet
jne_test_4	500	4	500	500	None	802.11b	4 subnets
jne_test_5	1,000	4	1,000	500	None	802.11b	4 subnets

Table 3.2
Scenario Performance Test Parameters

Scenario Name	Run Time (Seconds)	Total Agents	Compare to Real Time
jne_test_1	61	3	8.2x
jne_test_2	61	4	8.2x
jne_test_3	346	200	1.4x
jne_test_4	625[a]	1,000	0.8x
jne_test_5	2,500[a]	2,000	0.2x

[a] Extrapolated data (tests 4 and 5 were not run to completion because of performance restrictions of the test environment. It is recommended the lab test these to completion with their communications effects server cluster.)

Verification Tests

The objective of the verification tests was to explore message delivery rates across the interface. These tests considered the number of messages MANA generates and whether those messages are received across the interface in JNE. It further considered the whether the message was delivered in JNE (subject to the communication model) and then whether the message confirmation was transmitted back to MANA across the interface. Table 3.3 details the results of the interface verification tests.

The tests indicate that 100 percent of the messages received in JNE were received in MANA. The results further highlight that not all messages sent from MANA appeared to arrive in JNE for injection into the network. This is an artifact of the testing process. The value for "MANA messages received in JNE" comes from the JNE output files and is not logged in the external interface. Therefore, there may be any number of messages being buffered by JNE and not injected into the network before a simulation concludes or the messages may have been interrupted in the case of our extrapolated test cases. Further verification tests can be run in cases four and five in order to run the test to completion.

Table 3.3
Message Transmission–Verification Tests

Scenario	MANA Messages Generated	MANA Messages Received in JNE	Interface Transmission (%)	Messages Delivered in JNE	Messages Delivered in MANA	Interface Receipt (%)	JNE Message Completion Rate (%)	MANA Message Completion Rate (%)
jne_test_1	43	43	100	43	43	100	100	100
jne_test_2	34	34	100	34	34	100	100	100
jne_test_3	14,458	14,432	99.8	14,424	14,424	100	99.9	99.8
jne_test_4[a]	50,000	21,850	43.7	13,200	13,200	100	60.4	26.4
jne_test_5[a]	72,700	63,500	87.3	16,300	16,300	100	25.7	22.4

[a] Extrapolated results.

CHAPTER FOUR

Conclusions and Recommendations

The U.S. Cyber Center of Excellence, CDID, Cyber Battle Lab has a need for a suite of modeling tools that can enable exploration of the operational impact of the network. Current tools may be too deterministic and slow running to enable exploratory research at scale. To explore this need and provide one potential option, this report leveraged previous RAND work to interface two simulation tools, an agent-based force-on-force simulation called MANA and a high-resolution communication simulation called JNE. MANA's abstract, agent-based design can lower the cost of developing scenarios and enable a wide range of operational outcomes with minimal input from the modeler. Most importantly, battlefield entity decisionmaking is a core component of the model.

The interface has been designed with performance in mind and is capable of running significantly faster than real time to allow the modeler to maximize the number of scenarios he or she can explore. Further, the interface has been tested in concert with the U.S. Army's communication effects server, a large cluster capable of boosting simulation run times through parallelization. When interfaced with JNE, the pair creates a powerful exploratory tool.

Finally, there are a number of actions the Battle Lab, the Cyber Center of Excellence, and the Army can take to advance this capability and others like it:

1. *Use the interface to support an operational impact analysis*. The interface gives rise to a modeling approach that is particularly well suited to quick-turn analyses because of the relative ease of designing scenarios. When the alternative is to use no modeling, or to leverage Excel spreadsheets, MANA may offer an insightful middle ground. Further, MANA-JNE may prove insightful even in situations where there is time and money to use higher fidelity tools. To date, the interface has only been used as an exploratory tool for integration with other force-generation systems and demonstrated using an urban counter-insurgency mission.
2. *Explore alternatives to MANA*. For all of its benefits there are limitations. The Cyber Center of Excellence may benefit from new approaches to M&S, such as a hybrid cognitive and agent-based model that focuses on information and security and draws from the strengths of MANA. It may draw on the strengths of the deterministic models by including parallel execution and improved terrain fidelity and by allowing for agent scripting.
3. *Explore porting MANA (or similar agent-based models) to other types of network models,* such as the Navy Research Lab effort Extendable Mobile Ad-Hoc Network Emulator (EMANE) or NS-3. In doing so, the Cyber Center of Excellence could provide the

Army with a robust M&S approach, complementing existing solutions while relieving it of a licensing contract. Two important objective areas are low cost and fast operation.

4. *Revisit Regulation 5-11 and consider how validation can be achieved for different classes of M&S tools, such as agent-based*. The Army should also assess the validity of its M&S tools and determine whether its models are truly representative of the real world. Revisit whether the Army has sufficient focus on reactive behaviors in its validation approach.

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