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OBJECT-ORIENTED MODELING OF THE COMMUNICATIONS NETWORKS OF THE MAGTF

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The Marine Air-Ground Task Force (MAGTF) is supported by a communications system comprised of heterogeneous links and widely shared network resources. In this work, we describe our approach to modeling the MAGTF communications network. This model employs a new concept of workload modeling which we have developed. We provide a mathematical development of our measures of effectiveness and show how our model will be used to seek improvement in MAGTF communications performance.

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Object-Oriented Modeling of the Communications Networks of the MAGTF

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Abstract

The Marine Air-Ground Task Force (MAGTF) is supported by a communications system comprised of heterogeneous links and widely shared network resources. In this work, we describe our approach to modeling the MAGTF communications network. This model employs a new concept of workload modeling which we have developed. We provide a mathematical development of our measures of effectiveness and show how our model will be used to seek improvement in MAGTF communications performance.

1 Introduction

A Marine Air-Ground Task Force (MAGTF) is the organizational structure used for nearly all operational missions undertaken by U.S.M.C. forces. Independent of the size of the force, the MAGTF is always composed of four elements, the Command Element (CE), the Ground Combat Element (GCE), the Aviation Combat Element (ACE), and the Combat Service Support Element (CSSE). Whenever Marine Corps forces are called into action, they are organized under the MAGTF structure.

Experience indicates that the MAGTF is most effective in combat when employed as a single entity–a strategically mobile, combined arms, air-ground-logistics combat force under a single commander. To be effective, this commander must have the necessary command and control assets to direct the force.

The neurological component of the MAGTF is the Command, Control, Communications, Computer, and Intelligence system. Within this complex system, communications represents the most tangible, and the most hardware dependent subsystem. The MAGTF's ability to communicate effectively is fundamental to successful mission execution. Much effort has been expended evaluating performance of MAGTF's, as well as other military organization's, communication systems. Typically, these efforts involve stochastic modeling of the workload the communications system must handle. The performance is evaluated using analytic, approximation, Monte Carlo, or system simulation methods. To a large degree,

- the choice of evaluation tecnnology,
- the development and implementation costs, and
- the degree of acceptance and usability of the end product

are dictated by the degree to which the workload model reflects reality.

At one end of the fidelity spectrum, there exist models which have stationary arrival processes of message-sending requirements. These processes are typically stationary Poisson. This simple workload model is used because evaluating the resulting communications traffic process is analytically tractable. This approach usually allows for relatively inexpensive development at the expense of the degree to which the real system is accurately modeled, the usabilityof the results, and acceptance of the results by users. Examples of this apprcach are [2] and [6].

At the other extreme, we have models which attempt to simulate the evolution of combat, thereby inducing a realistic communications workload. Some of the drawbacks of this approach are readily apparent. In order to generate the communications traffic, this combat simulation must be of high resolution. Thus, realisticness comes with significant model development and programming costs. Such models require voluminous input data, to which confidence in model output is very tightly linked. Conclusions drawn from the results of high resolution combat models are valid only for the specific scenario used.

Furthermore, inclusion of details costs computational effort with each replication of the (obviously terminating) scenario, resulting in extremely large computing requirements for meager accuracy. This type of model displays hard-to-quantify effectiveness, as the engagement modeled can take several distinct turns during its evolution. Most frustrating, it becomes very difficult to attribute changes in performance to variations in input—experimental designs must be extremely weak. Examples of high resolution combat models for communications performance analysis are the Network Assessment Model [4], and a traffic simulator developed at NRL [5].

In this paper, we describe a model of MAGTF communications traffic which occupies the middle ground between the extremes of simple, analytically tractable Poisson models and high resolution combat models. Our model uses a paradigm of Marine Broad Operational Tasks (MBOTs), Broad Operational Subtasks (BOSTs), and Message Exchange Occurrences(MEOs). This framework is described in [8]. An MBOT is, as the name implies, a broad mission area that is undertaken by a group of units to satisfy a requirement. It is broken down into BOSTs, which represent the major component tasks required to fulfill the MBOT obligation. Each BOST comes with a set of communications requirements, its MEOs.

Among the details included in the specification of each MEO are the units and radio nets involved. Thus, we can generate communications traffic which is interdependent in a realistic way, without the onus of mimicking engagements. We may generate BOSTs in a static, stationary manner, and permit the MBOT/BOST/MEO structure to provide the realism we desire. Furthermore, we can generate BOSTs as dictated by a combat-model-like script and get all of the realism of a combat model without the large development costs. Finally, we may manipulate the rate of BOST generation in the time domain to facilitate a decision process which uses the model to compare alternatives.

In this work, we describe our object-oriented simulation model of the MAGTF communications process. We describe the development of appropriate effectiveness measure through the Modular C^3 Evaluation Structure (MCES) process (see [7]). Finally, we show some preliminary results generated by our model, and discuss the analysis of our model output.

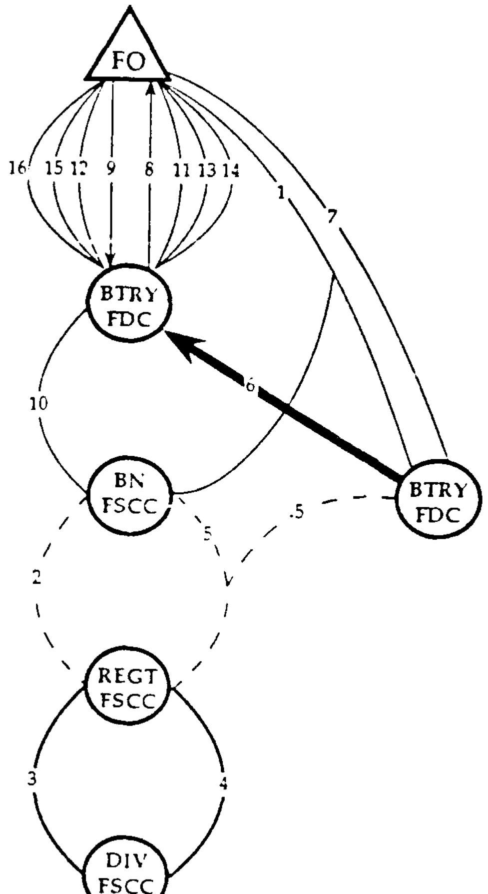

Figure 1: The Call For Fire BOST. Numbers correspond to MEO sequence numbers, while different line types indicate different radio nets.

2 Object Oriented Simulation

As our title indicates, we modeled the dynamic behavior of the MAGTF communications system using an object-oriented simulation language, in our case MODSIM II (see [3] for details of the MODSIM programming language). A full featured object-oriented simulation language has several advantages over non-object-oriented simulation languages, and over special-purpose simulation languages, for modeling our particular system.

The primary advantage of object-oriented language is, of course, the existence of the object data type, first described in [1]. Stated simplistically, an object is a record data type with procedures attached called methods. Fields of the object act like fields of a record with one fundamental exception, only the object's methods can alter the object's fields. This seemingly harsh restriction forces the programmer to standardize the interface to the object through a definition module for the object. Thus, an object enjoys a degree of autonomy. This autonomy ultimately leads to inherently reusable object programming.

Object-oriented simulation programmers make heavy use of object inheritance, where one object type assumes all the properties (fields and methods) of another, then alters some of these properties or adds more. This allows polymorphic object handling, where collections of objects of different object types share an interface.

For example, we might have two unit types, rifle company and tank platoon, which are object types derived from the more general unit object type. If we ascribe a method called **receive_order** to the unit object, then we can invoke **receive_order** for any object whose type inherits the unit object type. If, at some point in future development, we wish to add on Light Armored Infantry (LAI) platoon to the simulation, we may choose to inherit the properties of the tank platoon object as a starting point. We could tell the LAV platoon to receive_order without compunction, for we know LAV platoons inherited receive_order from tank platoons which inherited receive_order from units, where this capability was originally defined.

Like all process oriented (i.e. not discrete event) simulation paradigms, the object-oriented simulation modeling framework has occasion to *freeze* a process until some time passes, some condition becomes true, or some resource is available. The utility offered by object-oriented simulation is that this waiting is done by a method of an object. In MODSIM II, an object can have several concurrent methods waiting for different things (this capability is not shared by SIMULA, where an object may have only one waiting method). This again allows for autonomy of objects, promoting reusable object code.

In sum, object-oriented simulation provides several features which enable the simulation programmer to expand a simple model into one which is more complex, and to do so with confidence. This degree of modularity has enabled us to quickly develop our model using three programmer-authors, with graceful buildup due to the explicit interactions of the objects. Our simulation will be reusable by our sponsor to pursue further projects in MAGTF communications.

3 Major Model Components: Units, Nets, and Traffic Generation

The model we have developed has three fundamental object types, units, nets, and the traffic generation object. In this section, we provide the salient details of the model by describing the properties of these three object types.

3.1 Traffic Generation

In order to test the value of a specific communications architecture, we must stress the system in a realistic fashion. However, we wish our conclusions to be independent of a specific scenario of events. The use of the MBOT/BOST/MEO framework was briefly described in the introduction. The tasks that the MAGTF communications network will undertake have been identified and categorized in [8]. An example of an MBOT is *Artillery Call For Fire*, with the constituent BOST *Standard Call For Fire*. This BOST might be initiated by a Battery Forward Observer (BTRY FO). It involves the cooperation of the Artillery Battalion Fire Direction Center (BN FDC), the Battalion, Regiment, and Division Fire Support Coordination Centers (BN FSCC, REGT FSCC, DIV FSCC), and the Artillery Battery Fire Direction Center (BTRY ARTY FDC). The MEOs which are required to complete the *Standard Call For Fire* include the original call for fire, the clearing of the fire mission up the chain of command, the relaying of the clearance back down the chain, the spotting and firing directions exchanged between the BTRY FO and the BTRY ARTY FDC, and the end of mission and surveillance messages. There is some concurrency of MEOs in this mission, as well as a simple precedence structure between MEOs. This BOST involves four different nets, and is diagrammed in figure 1.

Each action is identified as a *Task* attached to one of the *Message Exchanges* of the MEO. Each specified message has associated with it a message format with the content identified message sender, receiver, radio net to be used, and duration. Some *Tasks* are pursued concurrently, while some have precedence over others.

To generate traffic for the MAGTF communications system, we generate a sequence of BOSTs occurring at each unit. These BOSTs will generate the specified MEOs, with the associated message traffic requirements and sequence.

Each unit, j, in the MAGTF has a rate of occurrence for each BOST, i, given as $\lambda_{i,j}$. Combination (i,j) initiates with this rate relative to the other BOSTs and the other units. Our traffic generation scheme must produce BOST initiations at each of the units at the specified relative rates.

For efficiency and centralization of control, we will generate BOSTs in a central process:

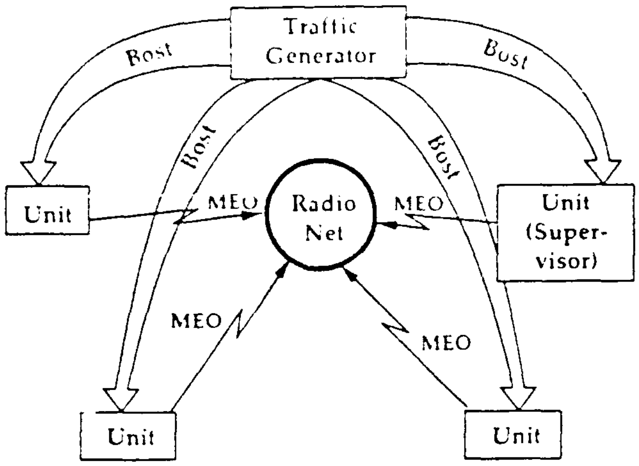

Figure 2: The relationship of the traffic generator, units, and the net resource for one net.

```
while (not TIME'S UP)
   sample DELAY with mean = 1/λr
   wait DELAY
   choose a BOST and UNIT
   tell UNIT to INITIATE_BOST
end while
```

Algorithm 1. The heart of central BOST generation process

where $\lambda = \sum_{(i,j)} \lambda_{i,j}$. For the present, we will assume that $r = 1$. Given BOST i and unit j, the BOST-unit combination (i,j) is chosen with probability $\lambda_{i,j}/\lambda$. If the central delays are chosen to be exponential, then each BOST- unit initiation is a filtered Poisson process. Otherwise, each time between BOST-unit initiations is a sum of a geometric number of *iid* delays. The distribution of BOST instances is pictured in figure 2.

3.2 Nets

Radio net transmission time is the only limited resource in our communications system model. A net may be thought of as a one-talker-at-a-time party line. Units connected to the net, called subscribers, all hear every message transmitted on the net, while only one subscriber may transmit at any time.

The nets in our model use a highest-priority-first discipline, which may be slightly more orderly than the real system. When an opportunity for transmission takes place, the net polls each of the subscribers and chooses a unit with a waiting highest-priority message at random. This queuing discipline is easily varied by changing the `ExecuteBusyPeriod` method of the net.

3.3 Units

The unit object type is the base type from which all of the MAGTF units are derived. Instances of unit objects range from a platoon object (≈ 45 marines) to a division object (≈ 19,000 marines and sailors). The communications equipment owned by a unit is housed in a radio array. Each radio is, in turn, connected to a radio net. The differences between units are the composition of the radio array, the rate of BOST initiation for each type of BOST, and the net membership of the radios owned by the unit.

Each unit is stimulated by the traffic generator by having a stream of BOST initiations sent to it. The unit then determines the first MEO of the BOST to pursue, finds all of the receivers which must receive the MEO, and submits the MEO for transmission on all of the nets required to reach the receivers. There are circumstances under which the unit will not be able to reach some of the intended receivers on the net specified in the BOST. Thus, the unit contains a complex routing mechanism which determines the sequence of units who will relay the BOST to the intended receiver.

Each BOST is pursued via the execution of MEOs between units. After a unit receives an MEO, it consults the BOST to determine the next MEO. It determines the appropriate net(s) using its routing mechanism, then submits this new MEO to the appropriate set of radios, one radio per radio net. The radio acts as a prioritized queue of MEOs, as well as possibly initiating busy periods of the attached radio net.

4 Measuring Effectiveness of the Communications Network

Each generated instance of a BOST has an object called a `Timer` attached. The `Timer` is created at the time the BOST is generated. It waits a BOST-specified amount of time called the `AllotedTime` of the BOST. During this time, the pursuit of the BOST is considered penalty-free. However, after `AllotedTime` has elapsed, the timer tells the `PenaltyAccumulator` to assess a BOST-specified `OneTimePenalty`. From this point forward, the lateness of the BOST costs an additional BOST-specified `PenaltyRate`. This rate is assessed until the BOST is completed successfully, or it expires due to excessive lateness.

Thus, the `PenaltyAccumulator` records a sample path of the penalty process. The long-run mean rate of penalty accrual reflects the degree to which the

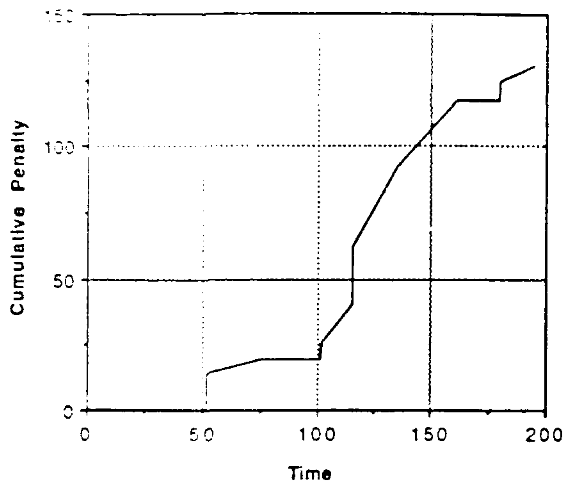

Figure 3: Example penalty process.

network is functioning properly. If a large amount of penalty is being accrued constantly, the BOST deadlines are consistently being violated. The sources of large consistent penalty accrual must be investigated, so that network designers can determine if the specified deadlines are unrealistic, if certain nets or units are consistently resource constrained, or if some BOSTs can be redesigned by increasing task concurrency or changing task structure so that deadlines can be met.

Note that we have allowed ourselves some flexibility in the pace at which workload is created by including the parameter r in algorithm 1. By manipulating r, we may be able to efficiently select the best performer from a set of proposed communications architectures.

5 Results and Analysis

The penalty process is the sum of the discrete jump process corresponding to the `OneTimePenaltys` which occur and the piecewise linear function with slope equal to the sum of the `PenaltyRates` being assessed at any time. An example of the beginning of a penalty process sample path is shown in figure 3.

For constant workload intensity r, we can analyze the penalty rate process using standard autoregressive methods, jackknifing, or using sample path sectioning (batching), to determine $\hat{p}(r)$ and $\hat{\sigma}_{\hat{p}(r)}$. In each case, we separate the sample path timeline into small intervals or sections which we use as samples. We can statistically or graphically determine the duration of the influence of initial conditions, which cause a negative bias in the estimation of $\hat{p}(r)$, see [9]. Let T be the time we simulate the process, and suppose that the initial conditions are determined to be without influence after τ^* time units have elapsed. We will collect our sample on the interval $[\tau^*, T]$, and construct the point estimate

$$\hat{p}(r) = \frac{p(T) - p(\tau^*)}{T - \tau^*}.$$

The variance of this estimate can be constructed via one of the standard methods mentioned above.

6 Conclusion and Future Research

In this study, we have proposed a new paradigm for workload modeling in military communications systems which reflects the dynamics and dependencies of the actual system, while not requiring a complex, high resolution combat model. This workload model is facilitated by the MBOT/BOST/MEO structure described in [8]. The authors of this document unknowingly share in the credit for our model.

We presented an object-oriented model of the communications system which exploits the MBOT-/BOST/MEO structure, measured the performance of the system through characteristics of a penalty accumulation process, and proposed methods for analyzing the properties of this penalty process.

The ultimate purpose of any modeling effort is the support of a decision. In our case, the sponsor wishes to allocate advanced radio equipment to some subset of the units in the MAGTF. Because the compatibility of the old equipment with the new is one-way, the new equipment must be allocated to every radio in a net for the net to be considered improved. Thus, we are faced with a ranking and selection problem where the options are the various feasible allocations of the advanced equipment to the nets within the MAGTF. In the near future, we will develop selection mechanisms that operate on continuous penalty processes, selecting the *best* allocation of advanced equipment while minimizing the amount of computational work required.

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Michael Bailey is an Assistant Professor of Operations Research at the Naval Postgraduate School (NPS). He received his Ph. D. from the University of North Carolina in 1988. His interests are applied stochastic modeling and analysis, operational reliability, quality assurance, and emerging technologies in simulation modeling.

William Kemple retired from the Marine Corps in 1985, where he was a C^3 specialist. He then pursued his Ph. D. in Applied Statistics at the University of California at Riverside, and is now an Assistant Professor of Operations Research at NPS.

Michael Sovereign was Chairman of the C^3 Academic Group at NPS from 1982-87. He was a Principal Scientist at SHAPE Technical Center, 1987-89, and returned to the NPS in 1989 to continue his career as a Professor of Operations Research.

Captain Michael West is a Marine Corps Infantry Officer and a student of Operations Analysis at NPS. **Captain Charles Chase** is a U. S. Army Engineer Officer and a student of Operations Research at NPS. Both students will graduate with Master's Degrees in Operations Research in September, 1991.

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