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TESTING, EVALUATING, AND ENHANCING NATO TACTICAL COMMUNICATIONS SCHEMES

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ABSTRACT

In this paper, we describe a simulation model called TACFONE-NATO, which simulates the constitution of a multinational NATO operational force and construction of the force's tactical communications system. This communications system is designed using Standardization Agreement (STANAG) 4214, which details methods for assigning area codes and phone numbers, and constructing the routing tables used to route calls. Our sponsor needed testing and evaluation of STANAG 4214's performance, diagnosis methodology for shortcomings, enhancements to the STANAG for lateral routing and formation movement. In this paper, we describe the methods we used to test, evaluate, and enhance STANAG 4124.

1 INTRODUCTION

The Joint Interoperability Engineering Organization (JIEO) is responsible for ensuring interoperability with United States allies, including North Atlantic Treaty Organization(NATO) allies. JIEO is also responsible for Standardization Agreements(STANAGs) and their implementation by the U.S., including STANAG 4214 (STANAG 4214, 1985), which deals with international routing and directory for tactical communications. JIEO and other NATO members have had difficulty in understanding this STANAG and there is concern over it's actual effectiveness.

STANAG 4214 specifies the routing prefixes and their applications in order to route calls within a tactical communications network, and from one tactical communication network to another. These networks are constructed using switches and gateways, each containing a table telling which numbers are reachable through that switch/gate. The aim of the STANAG is to provide a consistent, deducible, and unambiguous numbering scheme which will minimize the amount of information (i.e. the number of telephone numbers and the number of digits in the telephone numbers) held at each of the switches/gateways.

An individual network is a heirarchical tree with a designated *host* formation at the root. (Communications nodes are known as *formations* in NATO venacular, the heirarchical trees are called *networks*, and the entire system is called the *tactical communications system.*) Networks are connected together with an incomplete network of pairwise connections, see figure 1. As compared to the relatively simple task of constructing a civilian phone network, STANAG 4214 must be robust to the following:

- the composition of forces is never known beforehand, yet tactical communications must be established immediately when an operation begins;
- networks and subnetworks are comprized of units from different countries, and some pairs of country's communications equipment may not be compatable;
- each node in the network belongs to a within-country chain of command as well as a NATO chain of command, and communications must be smooth and simple in both chains;
- individual formations may move around in the NATO chain of command during the operation – they could move up or down the chain, or they could detach and reattach;
- the physical connection to a formation is often geographically determined, and might be different from its place in the NATO or within-country chains of command.

The STANAG was supposed to be designed to handle each of these circumstances. Our focus is determining if the STANAG number and routing methodology

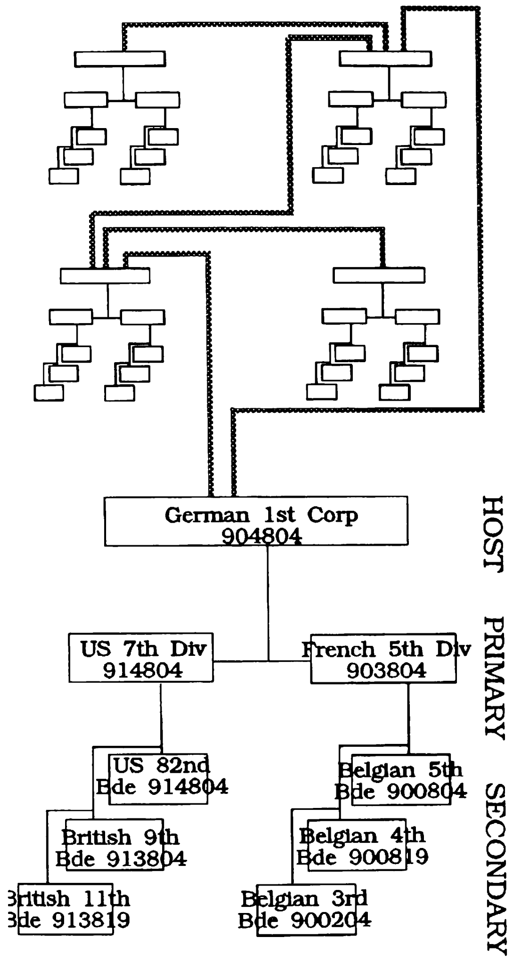

Figure 1: An Instance of Tactical Communication System. Note that the structure of physical links is a tree within one network, and a connected graph between hosts.

performs as it is supposed to over a very wide set of circumstances.

In addition, we would like to enhance the STANAG to allow lateral internetwork communications links. We would also like to produce a scheme that minimizes

- congestion in the network;
- disruption due to changes in configuration.

In the next section, we describe a model called TACFONE-NATO, which simulates the consitution of a NATO operational force, construction of the force's communications system, numbering of the force's formations, and construction of routing tables for each switch in the system. Following the description of TACFONE-NATO, we describe the methodology used to analyze the model's output in support of test and evaluation of STANAG 4214.

2 MODELING OF THE NETWORK

Our experience with deducible numbering schemes indicates that straightforward proof of the correctness of STANAG 4214 would be elusive. This is especially true when we allow formations to move within the force, and when there exist options for lateral physical connections. In addition, the sponsor indicated an interest in developing a general simulation model of the tactical communications system for exploration of future issues like congestion and response times. For all of these reasons, construction of an object-oriented simulation model of the tactical communications system's construction and employment was constructed. This simulation, called TACFONE-NATO, was constructed using MODSIM (MODSIM 93) was constructed.

TACFONE-NATO simulates a communication system and the crucial elements in order to allow the implementation of the protocols. Actual calls and their routing are made based on these protocols. Each call's paths are tracked to analyzed the effectiveness of these protocols.

2.1 Model Objects

What follows is a description of the basic building blocks of TACFONE-NATO. We model a communications system, comprised of networks, which are made of interconnected formations.

The communication system consists of a set of networks that are connected only through the highest level of each network. These networks in the are connected at least enough to comprise a minimumly connected graph of all networks, and may be connected up to a fully connected graph

A network is a hierarchically constructed tree of formations (nodes). The host of the tree, positioned at the root of the topological structure, is the only formation that is connected to other networks in the basic TACFONE-NATO. All calls for a formation within a network that are originated outside the network are routed through the host of the tree and down until the call reaches it destination. The networks have a maximum of three levels. The top level or host of the network is called the host level. The children of the host are the primary level. The children of the primarys are the secondary level. See figure 1 for an illustration. All incoming and outgoing calls for each formation are routed through their parent, unless the call is for one of the formation's children. Units at the host level are Corps-sized military units. The primary level equates to a division-sized unit and secondary level formations are brigade-sized unit. The STANAG 4214 protocol does not consider units of any smaller size.

Each formation is connected to it's parent and children (if any) via a switch, which is connected to a trunk, which connects to another switch at the other formation. Physically, the trunk can be a cable, satellite link, radio link, or any other communications link utilized by NATO nations. A switch is the connection point between a formation and a trunk. Each switch contains routing tables that list the formations that can be reached by routing a call through the attached trunk. If the connection is between formations of different countries, the switch contains a gateway. A gateway converts outgoing calls from the formation's national format to standard NATO format, and from NATO format to the appropriate national format for incoming calls, see figure 2.

2.2 Numbering the Communications System

Each formation in the force receives a ten-digit phone number. The number is comprized of a six-digit *routing prefix* and a four digit local phone number. The routing prefix is used to deduce a path for routing a call from one formation to another, and is the focus of our model. The prefix has two parts:

- a *National Indicator*, a three-digit code indicating the country the formation belongs to;
- an *Area Code*, which is nationality-specifc, and which is deduced from the communications system topology and the equipment available at the formation and its parent.

The routing prefix is often called a *NIAC*.

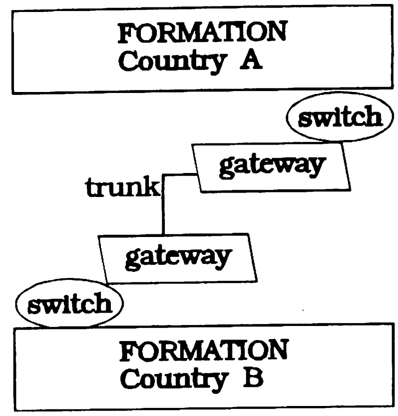

Figure 2: Gateways translate country-specific formats to NATO standard format and back again.

The equipment capabilities which are pertinent to formation numbering are

- whether the formation is single or multiple routing;
- whether the formation is duplicate-capable or not.

Equipment is considered multiple routing capable if it can route a call to another formation via several paths simultaneously. Once the call is successfully completed along any of these paths, all other attempts to route the call along alternate paths are terminated. Equipment that is single routing capable only can only route the call via one path. Hence, for single routing equipment, a call routed through an incorrect path will be always be a failed call. All single routing capable hosts or parents require all formations below them to have unique NIACs. Multiple routing capable units do not have this restricition.

Equipment that is duplicate capable is able to route a call to another formation with the same routing prefix as its own, while not-duplicate-capable equipment cannot. Therefore, all formations who are not duplicate capable require all other formations from their nation to have a different area code.

2.3 Generation of Communication Systems

TACFONE-NATO will either read in a user-defined force structure, or will randomly generate a force structure. If the force is user-defined, TACFONE-NATO can automatically number communications system, or the NIACs can also be defined by the user. This gives the user the flexibility to analyze a proposed numbering scheme that does does not follow the STANAG rules. When the communications system is generated randomly, the number of networks, formations and connections between networks are all randomly determined from preset bounds. The identity of the formations, including its nationality, is also randomly determined from the existing units that are available to NATO. Once the force has been generated and connected, the formations are numbered using the method discussed.

2.4 Building of Routing Tables

Once the communications system is generated and has been numbered, the routing tables are initialized for each trunk of each formation. Each network first updates its routing tables internally, then the switches connecting the networks initialize their routing tables. The basic model allows all paths that exist from one network to another to be reflected in the routing tables.

2.5 Generating and Routing Calls

Calls are generated from every formation to every other formation. The formation routes a call based on the physical limitations of communications equipment of his nation, as well as the contents of his switches' routing tables.

Between networks, calls are only routed via one path (single routed). The call tracks all formations that it is routed through in its path to reach its destination. As we shall see, there are several circumstances where a call fails to reach its destination, each creating a unique diagnostic problem.

3 ANALYSIS FOR A SINGLE COMMUNICATIONS SYSTEM

TACFONE-NATO described above will be excercised by executing the procedure shown in figure 3. This procedure will be henceforth known as a *single-system check*. Note that there is a one-time construction of the NATO force structure, and one assignment of nationality for each formation in a single-system check. In the sequel, we will execute ths single-system check over and over, using our ability to sample random variates to generate different force structures and nationalities for each check.

```
i)   construct a reasonable force
     composition for the operation,
     choosing
        country
        level of unit
        unit capabilities
ii)  construct a reasonable NATO chain of
     command for this force
iii) construct a reasonable set of physical
     connections between pairs of units
iv)  assign telephone numbers to each of the
     formations
v)   construct the proper routing table assoc-
     iated with each switch in each formation
vi)  attempt a call from each formation to
     every other formation, recording the
     outcome
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Figure 3: The sequence of tasks in a single-system check.

3.1 The Possible Outcomes and Assignable Causes for Errors

Each call can experience one of three outcomes, it can

1. complete as specified;
2. arrive at a formation which has no way of reaching the destination (dead end);
3. arrive at a formation which has already handled the call (loop).

Each simulated call n involves an originating formation f_0^n and a destination formation f_d^n, and records its journey through the network, building $\mathbf{f} = (f_0^n, f_1^n, \ldots, f_k^n)$, where f_i^n is the i^{th} formation relaying call n. If the call is completed, $f_k^n = f_d^n$. In addition, we record

$$X^n = \begin{cases} 0 & \text{if call complete} \\ 1 & \text{call at dead end} \\ 2 & \text{call loops.} \end{cases} \tag{1}$$

The path $\mathbf{f}$ and the value of X indicate where the trouble-causing formation switches are. Table 1 shows some prime suspects for different completion outcomes.

3.2 Analyzing Error Data

Our goal is to determine the causes of incomplete calls. Incomplete calls arise because of one or more mistakes in the formation of the routing tables in the

X^n	prime suspects
1	f_{k-1} outgoing switch overstates formations reachable f_k has at least one switch which has an ommission
2	loop includes $(f_i, f_{i+1}, ..., f_k = f_i)$ one outgoing switch in loop should omit at least one entry
1 or 2	f_d numbered incorrectly

Table 1: Likely causes for failed calls.

switches, or in ambiguous or incorrect phone numbering of the formations. Each formation has attributes which determine the method used to number it, and also determines the situation in which it forms its routing table. The attributes of a formation are

- ROLE : Host(H), Primary(P), or Secondary(S);
- NATV: true(T) if same nationality as parent, false(F) if not;
- DUP: true(T) if duplicate capable, false(F) if not;
- RT : both parent and host are single routing(SS), host is single routing, while parent is multiple routing(SM), both host and parent are multiple routing(MM), or host is multiple routing but parent is single routing(MS).

Each failed call is caused by some shortcoming of the numbering rules or routing tables which arise from some (possibly incomplete) combination of these attributes. For example, it is possible, albeit improbable, that something is wrong with the rule for numbering any secondary formation. It is also possible that secondary formations which have nationalities which are the same as their host but different from their parent, and whose parent is multiple routing are not all numbered correctly. We wish to distinguish the precise combination of attributes under which calls are not reliably routed through a formation.

3.3 Algorithmic Cause Identification

For each failed call n, let

$$a^n_{ROLE,NATV,DUP,RT} = \begin{cases} 1 & \text{if a prime suspect formation for call n has properties ROLE, NATV, DUP and RT} \\ 0 & \text{if the combination ROLE, NATV, DUP and RT doesn't describe a prime suspect for call n} \end{cases} \quad (2)$$

Let $a^n_{ROLE,.,.,.}$ be a similar indicator variable for the ROLE of each prime suspect for call n, with $a_{.,NATV,.,.}$, $a_{ROLE,.,DUP,.}$, and $a_{ROLE,NATV,.,RT}$ be similarly defined.

Let $z_{ROLE,NATV,DUP,RT}$ be a decision variable which follows the following:

$$z_{ROLE,NATV,DUP,RT} = \begin{cases} 1 & \text{problems arise for formations with properties ROLE NATV, DUP, and RT} \\ 0 & \text{formations with properties ROLE, NATV, DUP, and RT are handled correctly} \end{cases} \quad (3)$$

Let us refer to these variables as cause conclusion indicators. If one conclusion is a refinement of another (eg. H,.,.,SS is a refinement of H,.,.,.), we refer to the moregeneral conclusion indicator as *composite* conclusion, while the refinement is a *constituant conclusion* of the more general one. We will use these variables in a simple set-covering-like optimization which will have as its solution the likely set of causes for the failed calls.

Consider the following mathematical program constraint set:

$$1 \leq \sum_{\Omega} a^n_{ROLE,NATV,DUP,RT} z_{ROLE,NATV,DUP,RT} + u_n, \quad (4)$$

where Ω is the set of all possible combinations $ROLE, NATV, DUP, RT$ with $ROLE \in \{H, P, S, .\}$, $NATV \in \{T, F, .\}$, $DUP \in \{T, F, .\}$, and $RT \in \{SS, SM, MS, MM, .\}$. The u_n corresponds to not being able to assign a cause to failure n. By convention, we call this a zero-factor conclusion. We seek a combination of z's which *cover* all of the failed calls. Furthermore, we prefer to have information which is as precise as possible – accepting $z_{S,.,.,.}$ as 1 is less desirable than accepting $z_{S,T,T,.}$, which, in turn, is less desirable than accepting $z_{S,T,T,SS}$. We wish to produce a set of decision variables which give us as much information as possible. On the other hand, if we observe that $z_{S,T,T,SS}$, $z_{S,T,T,SM}$, $z_{S,T,T,MS}$ and $z_{S,T,T,MM}$ are all 1, we really have a situation where they really should all be 0, and $z_{S,T,T,.}$ should be 1.

Finally, we build a set of fairly complicated constraints which ensure that if all of the constituant conclusions are believed, the composite conclusion is chosen as well. However, since there would then be a redundancy, the cost structure will ensure that the constituant conclusions will be dropped when possible.

The objective function, given as

$$min \sum_{\Omega} c_{ROLE,NATV,DUP,RT} z_{ROLE,NATV,DUP,RT} + \sum_{n=1}^{N} c_{.,.,.,.} u_n \quad (5)$$

completes the specification of our mathematical program. We solve this optimization using some of the methods found in (Balas, 1980).

3.4 Graphical Cause Identification

Identifying causes for failed calls may also be done using a graphical display we have developed. The users of our system may be interested in using their intuition to identify causes, and this display also provides a usable problem diagnosis tool. Finally, our system is also of use to the sponsor for other activities besides STANAG 4214 testing, and these uses demand a topographical picture of the communications system.

We have developed a method for generating failed call displays like the one shown in figure 4. Using this display, the user may show failed calls by

- formation of origin;
- destination formation;
- prime suspects.

Once failures are displayed, the user is allowed to *weed* the failures by attributed cause. He/She does so by building a set of identified causes, essentially picking some of the z's from the algorithmic method. Once this set is constructed, the failure display is altered so that only unexplained failures remain. This elimination process is iterative, with the user making choices like our set-covering-problem solver.

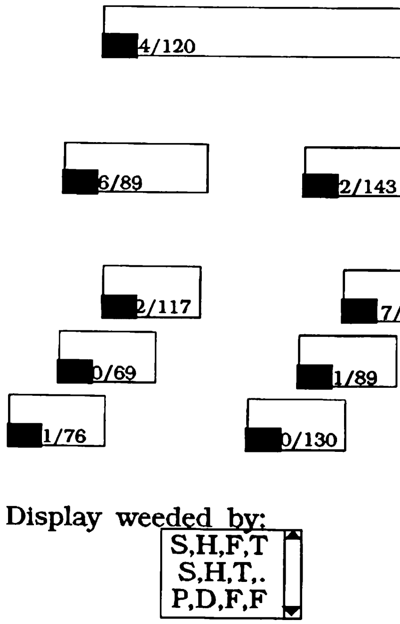

Figure 4: Failed calls display. The display shows the failed calls which remain unexplained after the indicated failure indicators are considered.

4 RANDOMLY GENERATED FORCE STRUCTURES

All of the above methodology applies to a single-system check, where the same nationalities and force structure are used. Once we accomplish the single-system check, we wish to construct a new force structure, choose new nationalities for the units, and iterate. This process is shown in figure 5. We carry over the set of identified causes for each new system.

5 SOME RESULTS

Results from this model can be clearly stated, understood, and appreciated. TACFONE-NATO generated thirty force structures using units likely to be involved in NATO operations. Using STANAG 4214 routing and numbering rules alone, only 85.9% of the possible pairs of formations could sucessfully communicate! The remaining 14.1% of the calls failed. The failures were diagnosed using the set covering method described, and found to be of two major categories

- looping among host formations;
- multiple-routing hosts with single-routing primaries and a particular arrangement of same-country, duplicate capable secondary children.

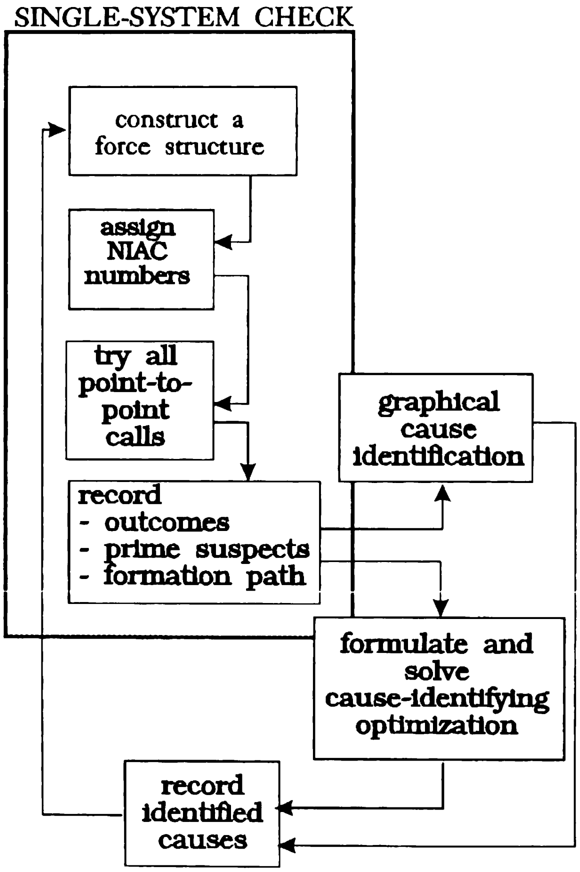

Figure 5: Analysis process for replicative simulation of force structures.

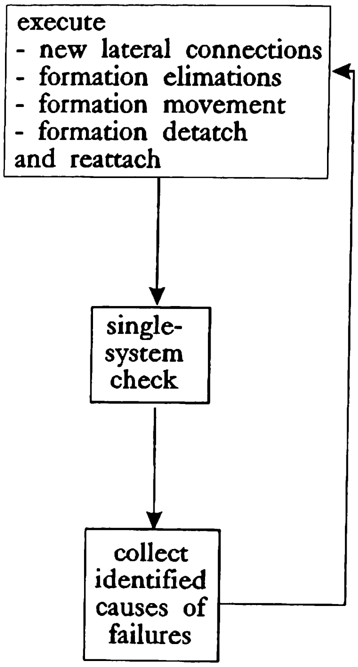

Figure 6: Analysis process for replicative simulation of force structures with the extra movement and lateral connection capabilities.

6 EXPANDED COMMUNICATIONS SYSTEM ANALYSIS

We wish to enhance the STANAG 4214 method for numbering formations and constructing routing tables. These additions are designed to address

- loop-prevention rules for constructing routing tables;
- formations establishing lateral connections;

This is accomplished in our model by manipulating the system as shown in figure 6. What is intersting about the extra rules we developed is that they are enforced *after* the basic STANAG 4214 rules are employed. These new rules involve the reconstruction or restriction of routing tables, changing the way formations route calls, *and* renumbering formations.

The resulting improvements in communications reliability are shown in table 2.

As can be seen, we successfully addressed the looping calls and the other problem described above. Furthermore, we were able to allow arbitrary lateral connections by adding another routing rule without loss of reliability.

SETTING	SUCCESS RATE
STANAG 4214 alone	85.9
+ anit-looping rules	99.6
+ fix of diagnosed rule problem	100.0
with lateral connections	100.0

Table 2: Results from Enhancing STANAG 4214.

7 CONCLUSION

In this work, we described an analysis process for determining the correctness of the NATO tactical communications system protocol STANAG 4214. We described a simulation model used to generate instances of NATO operational force structures. The model, called TACFONE-NATO, generates sets formations which are likely suspects for misnumbering or misrouting. It also generates a set of graphics which the user can employ to uncover probable causes for any failed calls, and a formulated set-covering optimization problem. Solving this optimization produces a set of probable causes of failed calls.

This system has proven useful in fulfilling the requirement stated by our sponsor, JEIO. We have uncovered a set of errors in STANAG 4214, and have constructed a set of remedies which ensure complete reliability of the protocol. We have extended STANAG 4214 to address arbitrary lateral connections, and have produced rules which allow lateral connections without loss of reliability. We also have indications that the sponsor will use the model to do contingency planning at JEIO, as well as for supporting communications equipment procurement decisions in the near future.

ACKNOWLEDGEMENTS

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AUTHOR BIOGRAPHIES

LT. MICHAEL DORKO, USN AND LT. ROBERT SCHULTZ, USN are students of operations research at the Naval Postgraduate School. Both are in the final phases of their degree programs, where they are obliged to write Masters' theses. To this end, they have pursued NATO tactical communications analysis with JEIO sponsors, collected all of the data, and written most of the code for the TACFONE-NATO model.

MICHAEL BAILEY, WILLIAM KEMPLE, AND MICHAEL SOVEREIGN are professors of operations research at the Naval Postgraduate School. Together, they have pursued research in modeling military communications systems for three years, and have enjoyed the synergy provided by their combined operational and technical expertise. Group efforts have included supporting equipment upgrades for Marine Corps single-channel radio networks, constructing a classification scheme for models of strategic defense, and the work represented by this paper.