A Comparison of Deterministic vs Stochastic Simulation Models for Assessing Adaptive Information Management Techniques over Disadvantaged Tactical Communication Networks

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Abstract

A test bed is being designed and implemented at DRDC Valcartier[1] to study the effect of information management techniques, applied at the level of the application database in each participating node of a simulated tactical radio network, on the quality and timeliness of information distributed across the network. This paper describes key concepts and architecture for a test bed that was conceived to support these information management studies in a realistic simulated battlefield environment. Two basic simulation models were considered for the test bed. In the first, the battlefield and communications components of the simulation model are fully deterministic. The battlefield component is implemented as an event-rich script consisting of an invariant sequence of battlefield events. The communications component is based on a single throughput-delay curve or family of such curves. In the second simulation model, the battlefield component remains deterministic while the communications component introduces a stochastic element to produce a more realistic characterization of the communication channel(s). The communication model is based on a Markov process characterization of the communication link(s). This gain in accuracy is realized at the expense of introducing a probabilistic element in the model. The advantages and disadvantages of each approach are discussed in the context of the information management studies they must support.

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[1] formerly known as DREV (Defence Research Establishment Valcartier); name change effective 1 April 2002.

1. **Introduction**

On the tactical battlefield, the means of communication between vehicles or dismounted soldiers is generally a line-of-sight radio operating in the VHF or UHF band. The advent of tactical digital command and control systems has generated a requirement to distribute significant quantities of digital data over these radio systems. Initial experience with passing tactical data in digital form over Army radios has highlighted the inadequate data capacity of the wireless channels. Armies are learning that, on an information-hungry battlefield, demand for information in digital form will, at least for the foreseeable future, exceed channel capacity.

One of the major reasons for introducing digital command and control systems into the tactical domain is that they promise increased battlefield awareness through a more systematic and automated distribution of relevant data than is possible with a voice-based communication system. To deliver on this promise, however, the communication infrastructure must be capable of distributing digital data among participating mobile command and control nodes with high fidelity and with a timeliness appropriate to the operation (i.e. it must meet the commander’s critical information requirements). To be useful, critical information must be passed quickly enough to permit the friendly commander, and the staff that he commands, to stay and act within the decision cycle of the enemy commander.

In the tactical domain, sharing of information on an ‘all-informed’ basis is highly desirable, if not essential, to avoid a single point of failure and ensure continuity of operations. Under this exchange model, neighbor nodes attempt to maintain exact copies of each other’s database via asynchronous data replication. When the communication channels are characterized by low and variable throughput and unreliable connectivity, maintaining exact copies of each other’s database (‘full synchronization’ of database content) via asynchronous data replication can be impossible. Due to the imperfect communication channels, it is likely that, over time, the databases will drift out of synchronization and the users will be unaware that this is happening. Users will believe that they are sharing the same situation picture, when, in fact, they are not. Such a characteristic, if detected, can undermine confidence in the system. Undetected, this characteristic may have deadly consequences.

In such a communications environment, it is important to build into the command and control system information management strategies that can adapt to changing battlefield and network conditions without user intervention so as to optimize the flow of priority and high-value information between nodes regardless of the state of the communication channel.

At Defence R&D Canada - Valcartier, a test bed is being implemented to study the impact of information management techniques on the quality and timeliness of information distributed across the tactical battlefield [Gibb and St-Jacques, 1999]. From a quality of information perspective, the consistency of the information stored and used at various levels of command is a major area of concern. The test bed will support the development and execution of Concept Development Experiments (CDEs) aimed at improving information dissemination and information quality on the battlefield. Key components of this test bed include a battlefield model and a tactical radio communication model.

Two basic simulation models were considered for the test bed. The first is characterized by battlefield and communications components that are fully deterministic. In the second, the battlefield component remains deterministic while the communications component introduces a stochastic element to produce a more realistic characterization of the communication channel(s). This paper discusses the advantages and disadvantages of each approach in the context of the information management studies each must support.

2. **Terminology**

The terminology definitions below are taken from [Banks and Carson, 1984].

Discrete-event systems simulation is the modelling of systems in which the state variable changes only at a discrete set of points in time. The simulation models are analyzed by numerical methods. A simulation model is a particular type of mathematical model of a system. Models can be classified as static or dynamic, deterministic or stochastic, and discrete or continuous.

A *static* simulation model, sometimes called a Monte Carlo simulation, represents a system at a particular point in time. *Dynamic* simulation models represent systems as they change over time.

Simulation models that contain no random variables are classified as *deterministic*. Deterministic models have a known set of inputs which will result in an unique set of outputs. A *stochastic* simulation model has one or more random variables as inputs. Random inputs lead to random outputs. Since outputs are random, they can be considered only as estimates of the true characteristics of a model. In a stochastic simulation, the output measures must be treated as statistical estimates of the true characteristics of the system.

A *discrete model* is one in which the state variable(s) change only at a discrete set of points in time. A *continuous model* is one in which the state variable(s) change continuously over time.

This paper describes a *discrete-event system simulation* in which the simulation model is *dynamic* and *discrete*, with both *deterministic* and *stochastic* components.

3. **Information Management Techniques**

The information management techniques being studied are techniques that will exploit and act on data in the local database within a tactical node. The techniques can take two basic forms - those which prepare information in the most efficient possible form for transmission, and those which limit what is transmitted and/or when it is transmitted. As simple examples, a data compression algorithm would fall into the first category. A rule which inhibits the broadcast of an ‘own position’ report from a vehicle whose position has not changed would fall into the second category. For the most part, the techniques will be implemented as expert rules tied to individual data elements in the database using the mechanisms of triggers and stored procedures. The purpose of the expert rules is to build into the tactical nodes information exchange control mechanisms which will adapt themselves without user intervention to changing operational context and/or to changing conditions on the communications network.

In principle, it is possible to analyze each information management technique individually and to project its impact on the battlefield for certain limiting cases. However, the information management techniques are adaptive in nature and intended to be applied together. The combined effect under realistic operational conditions is extremely difficult to assess unless those conditions are simulated with some degree of fidelity. What is required is an infrastructure which permits a) realistic tactical scenarios to be played out, b) behavior of the communications channels to be simulated with fidelity, c) information management techniques to be applied throughout the scenario run, and d) data to be recorded during the scenario run which will allow the impact of the techniques to be assessed. The test bed will provide that infrastructure.

4. Test bed Concept

4.1 *Architecture*

The test bed will consist of a set of simulated tactical nodes (maximum thirty-two, four shown) linked together through a central server node [Figure 1]. The latter node will contain a software module that simulates relevant characteristics of the wireless communication system. Scripted tactical scenarios, spanning a spectrum of tactical Army operations, will be played out which require information in the form of data transmissions to be passed between simulated nodes through the communications system simulator. The simulated nodes will have just the functionality necessary to mimic relevant functionality of true tactical command and control nodes (e.g. a geo-referenced map display with moveable icons). The scripted scenarios will be capable of automated execution without men in the loop through use of scripts, or manual execution with men in the loop stationed at the consoles of the simulated tactical nodes.

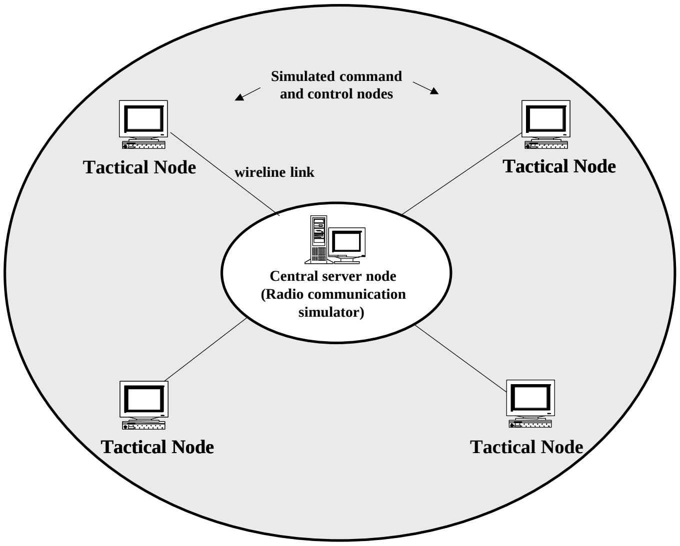

Figure 1. Test Bed with Radio Communications Simulator

The test bed will permit a second mode of operation (Figure 2) in which a tactical radio is interfaced to each node and the data communications related to scenario events are broadcast over the radio system. In this mode, the wireline links between the nodes and the central server are maintained to ensure synchronization of scenario execution across nodes and to enable inspections of database content and data logging during pauses in scenario execution.

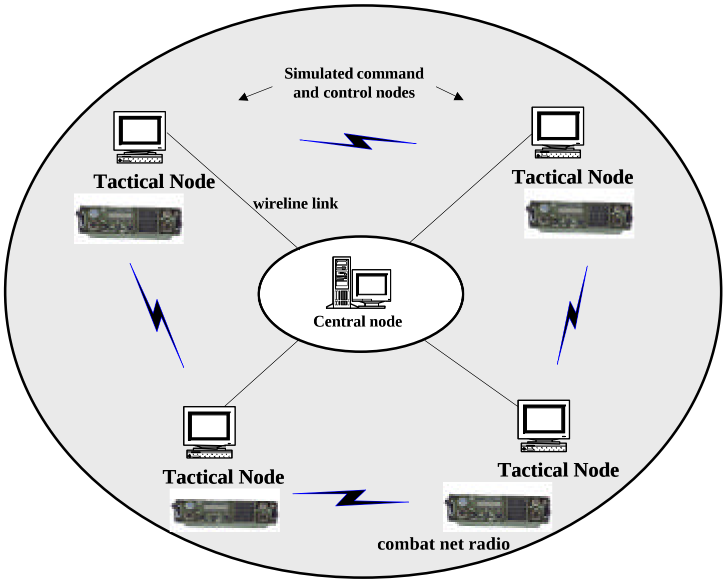

Figure 2. Test Bed with Tactical Radios

4.2 *Information Exchange Model*

In the tactical domain, sharing of information on an 'all-informed' basis is highly desirable, if not essential, to avoid a single point of failure and to ensure continuity of operations. If neighbor nodes have exact copies of each other's database, a node can assume a neighbor node's role, when necessary, without requiring a massive one-time data transfer. As well, a node disconnected from the network can recover lost data from any neighbor node upon reconnection.

Information exchange on the tactical battlefield based on database updates, as described by Chamberlain [Chamberlain, 1996], offers the potential for a substantial improvement in the utilisation of available bandwidth and strong support for nodal autonomy. With this approach, the database schema supports a situational model of the battlefield. Each local node maintains its own situation model in its database. The primary role of tactical data communications is to update each other's database rather than to exchange messages. In a bandwidth-limited environment, database-to-database exchange through replication of database transactions is generally more bandwidth efficient than the exchange of structured military messages. Database replication exchanges only new or modified data while military messages, which must be semantically complete, tend to exchange both modified and unmodified data.

The test bed will implement an 'all-informed' exchange model involving asynchronous replication of database updates.

4.3 *Effect of Communications Channel*

In an ideal communications environment, characterized by perfect connectivity and zero latency, asynchronous replication will occur with almost zero latency and database content will synchronize across nodes with almost zero latency – a true 'all-informed' model.

In a non-ideal communications environment, connectivity is imperfect, bandwidth is finite, and latency is non-negligible. Use of asynchronous replication means that a portion of the database content at any given time will not be synchronized (i.e. values for certain data elements will not be consistent across all network nodes), An efficient replication mechanism, given reasonable connectivity and adequate bandwidth, can ensure that synchronization will occur with low latency and that the portion of unsynchronized data will be kept small and relatively constant. Users will not have exact copies of each other's database, but will have almost-exact copies.

When communication channels are characterized by low and variable throughput and unreliable connectivity (the subject of this paper), maintaining exact or almost-exact copies of each other's database via asynchronous data replication is not realistic. There is a risk that the databases will drift increasingly out of synchronization and the users will be unaware that this is happening. Users will believe that they are sharing the same situation picture, when, in fact, they are not.

4.4 *Measurements*

The purpose of the automated information management techniques is to ensure that, under the conditions just mentioned, the tactical nodes will manage information exchange intelligently so as to (1) minimize the quantity of data transmitted, and (2) ensure that data values for information of high operational importance remain fully synchronized across the nodal databases.

Quantitative assessment of the impact of these techniques requires that the test bed provide a controlled environment for the execution of experiments, i.e. that experimental conditions and results be highly reproducible. Measurements made using the test bed infrastructure must provide information about database states during scenario execution for the following three cases:

(1) Perfect communication channels;
(2) Communication channels characterized by low and variable throughput and unreliable connectivity, with no intelligent information management techniques applied;
(3) Case (2) but with intelligent information management techniques applied.

Differences in data values for cases (1) and (2) provide a quantitative measure of the effect of the imperfect communication channels on the de-synchronization of database content.

Differences in data values for cases (2) and (3) reflect the success of the information management techniques in counteracting the negative effects of the communication channels.

Both sets of difference measurements are important. It is necessary to have a quantitative understanding of the effect of the communications channel on database de-synchronization for different communications traffic conditions and states of network connectivity before the positive impact of the information management techniques can be reliably evaluated.

5. **Deterministic vs Probabilistic Battlefield and Communications Models**

Clearly, it is not possible to make meaningful measurements for all three of the above cases during a single scenario execution. To measure the differences referred to above, it must be possible to repeat the scenario several times. Two approaches are considered viable.

In the first approach, the battlefield model described in the scenario is fully deterministic (i.e. capable of generating the identical sequence of battlefield events each time), as is the communications model. With this approach, the scenario is repeated with perfect fidelity three times, once for each of the above cases. It is then possible to attribute the difference in observed results uniquely to the effect of the applied information management technique, because all other experimental parameters are identical from case (2) to case (3).

In the second approach, one or both of the battlefield component and communications component of the simulation model are stochastic in nature. Each time the simulation is run it will have a slightly different outcome, even if the inputs are the same. This characteristic makes it impossible to correlate differences in observed results uniquely with the effect of the applied information management techniques. To observe statistically-meaningful differences, it would be necessary to repeat each of cases (1) through (3) many times and to perform a statistical averaging so that randomly occurring effects are averaged out. Such an approach significantly increases the amount of effort required, both to run the experiments and to analyze the results.

For the battlefield component of the simulation model, the primary advantage of a stochastic model is that such a model more accurately characterizes the unpredictable nature of the tactical battlefield. It also helps to ensure that observed results are not unduly biased by the particular choice of events comprising the scenario. However, the risk of biased results from use of a deterministic battlefield model can be reduced by ensuring that the model contains a rich mix of events judiciously selected to minimize such bias. Also, where bias is suspected, it may be possible to test for bias by modifying a portion of the scenario or by introducing stochastic behavior for certain variables, then re-running the experiment. A fully deterministic battlefield model was selected for the test bed experiments because the advantages of full control over the sequence of scenario events and the repeatability of those events far outweighed any disadvantages.

For the communications component of the simulation model, on the other hand, one is trying to characterize a real physical system whose behavior has an intrinsically random component. In this case, the risk of obtaining biased results through use of a simulation model which does not accurately characterize the behavior of the communication channel is a more serious issue. Options for modelling the communications channel behavior, and the advantages and disadvantages of each option, are discussed in Section 7.

6. **Deterministic Battlefield Models**

The battlefield model consists of a list of events occurring in a specific sequence on the battlefield in the context of a tactical scenario, e.g. a tank moving from position A to position B, or a radio communication between vehicle X and vehicle Y. A deterministic battlefield model has the property that the sequence of events remains invariant each time the scenario is executed.

There are two basic approaches that can be used to generate a deterministic battlefield model. In the first approach, one or more military subject matter experts (SMEs) develop the broad outline of a tactical scenario, and the SMEs then generate the detailed script of battlefield events and event timings to populate the scenario. Each battlefield event and (where appropriate) event timing is captured into a script file. A software tool then reads the script file and converts the scripted events into a format that can be understood by the communications component or information management component of the test bed. In the second approach, a software application that allows simulation of battlefield activities is used to generate the series of events. If the application can be interfaced directly to the test bed through an interface module, the generated events can be used to stimulate directly the communications component and information management component of the test bed. If the application cannot be interfaced directly to the test bed, or the simulation is not directly useable because it has a stochastic component, the events and event timings can be captured in a log file. It may then be possible to interface the log file to the test bed through a software module and to use the log file as the source of the deterministic battlefield model. If the exact event sequence generated by the application is not what is desired, but the log content can be cast into human-readable form, a subset of the logged events can be read by subject matter experts and (following the first approach described above) used to generate a script file.

Two software applications that may be useful for generating the deterministic battlefield model are JANUS and ModSAF (Modular Semi-Automated Forces). Both have stochastic components and so cannot be used directly to stimulate the communications component and information management component of the test bed. However, log files which they generate can be useful.

6.1 ***JANUS***

JANUS is a warfighting simulation that challenges commanders to plan and interactively fight battles against real world opponents. JANUS can see the opposing sides, but the players cannot. Commanders plan and execute their battles on digitized maps anywhere in the world. The warfighter's view is a two-dimensional map-like display that includes grid lines and graphic control measures. To the weapon systems in the field, however, the terrain is three-dimensional, with elevation and contour affecting maneuverability and lines of sight. Individual weapon systems engage the enemy with the appropriate weapon or ammunition based upon range, target type, and ammunition remaining. JANUS is an interactive, two-sided, closed, stochastic, ground combat simulation. Data concerning discrete battlefield events and the position and status of weapon systems are logged continuously throughout the scenario. These data can be used to replay the scenario for post-mortem analysis. It is not clear at time of writing if scenario events recorded in the JANUS database can be exported to another system in an useful format.

6.2 ***ModSAF***[2]

ModSAF is an interactive, high resolution, entity level simulation that represents combined arms tactical operations up to the battalion level. It is comprised of a set of software modules and applications used to construct Advanced Distributed Simulation (ADS) and Computer Generated Forces (CGF) applications that provide a credible representation of the battlefield, including physical, behavioral and environmental models. ModSAF is based on two types of modeling, deterministic and stochastic. Deterministic modeling in ModSAF is applied to the defined entities behavior (e.g. attack the enemy if the distance to the target is less than a fixed value). Stochastic modeling is applied to events such as detecting and firing on an enemy. Because of the stochastic component, two runs with the same entities and the same initial values will result in different simulation activities. The ModSAF data logger records the simulation packets of any protocol family transmitted on the simulation network. This capability could permit the creation of a scenario file that could generate an invariant battlefield model for all planned test bed runs.

7. **Communications Models**

The role of the test bed's Radio Communication Simulator (RCS) is to approximate the impairments that the battlefield communication environment would cause on the data/packet flow. Information representing the battlefield communication environment must be fed into the simulator in order that it can produce the associated impairments in the information flow.

The RCS consists of two main elements: the models used to simulate (1) the network communication protocols and (2) the radio communication channel. Network communication protocol models are built into most simulation packages and will not be discussed further here. The radio communication channel model is emphasized in this paper. The channel model characterizes the external (communication) environment in which a wireless system/network operates, i.e. the communications channel between a pair of antennas. The channel accounts for propagation effects such as path loss, rain absorption, multi-path, fading, diffraction, refraction, and scattering, as well as general background noise. In the widest sense, the channel may also account for sources of interference when these are treated in aggregate.

There are three broad categories of channel models: discrete, continuous and ray tracing models. Primarily for reasons of computational efficiency, a discrete channel model approach has been selected for the Radio Communication Simulator.

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[2] In the near future, the American Army will retire ModSAF and replace it by OneSAF. OneSAF is a next generation Computer Generated Forces (CGF) that can represent a full range of operations, systems, and control processes from the individual combatant and platform level to battalion level. Unit behaviors will be modeled to the battalion level for selected units, and command entities will be modeled to the brigade level. OneSAF will have a variable level of fidelity that supports models and simulations (M&S) domains. It will represent specific activities of combat, command, control, communications, computers, and intelligence (C4I), combat support, and combat service support. It will also employ representations of the physical environment and its effect on simulated activities and behaviors.

Information about the communication environment that must be fed into the Radio Communication Simulator may take many forms, from simple or complex mathematical models to simulation or experimental curves. This section discusses three different options to provide these data to the simulator, namely:

- a single Throughput/Delay (T-D) curve;
- a family of T-D curves; and,
- a Markov process.

A key constraint under which these alternatives must be evaluated is that the results of a simulation must be reproducible given the same experimental parameters.

7.1 *Single T-D Curve*

While the notion of network throughput is unclear, both throughput and delay have clear meanings for a communication link. In network analysis and simulations, T-D curves are often used as a high level model (or abstraction) of a communication link. The underlying assumption, that throughput and delay are a full characterization of the communication link, is valid for some network studies but is not valid in all situations.

Many simulation packages used to produce T-D curves (e.g. OPNET, QUALNET, NS-2) implement a discrete channel model which assumes independent, randomly distributed errors. This assumption is often not valid for a wireless channel. In addition to this limitation, a number of assumptions need to be made to obtain a T-D curve. Some of the required assumptions are:

Network wide:
a. distribution of traffic sources/sinks, i.e. who can originate and receive information;
b. network load and the mix of voice/data in the load (i.e. traffic profiles); and
c. network topology (number of nodes, distance between pair of stations, who is connected to whom (wired network)).

Each network node:
a. An application traffic model for each workstation
    i. distribution of message/packet sizes
    ii. distribution (frequency) of message/packet transmissions
    iii. distribution of voice/data traffic
    iv. voice/data mix
b. (possibly) error-statistics (at least bit error rate) for each individual link between a pair of stations

An example T-D curve is depicted in Figure 3. For a T-D curve to be valid, a large statistical sample of the channel conditions (if link error statistics are unspecified) must be exercised. For the result to be statistically stable, the simulation must be run for a sufficiently long time. The T-D curve is a statistical curve resulting from a wide range of channel conditions, averaged both over system parameters and over a long time period. Many of the interesting channel/user features vanish in this process. Variability, including both good and bad extremes, is lost.

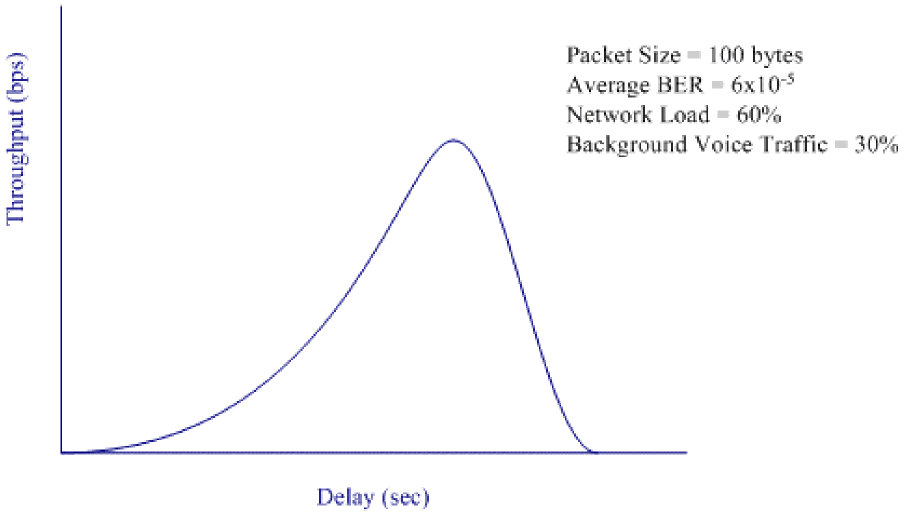

Figure 3. Illustration of a Throughput/Delay Curve

A second issue is that the throughput/delay curve is valid only for a range/mix of test bed system parameter values that are consistent with the assumptions made in the derivation of the T-D curve (message/packet sizes, characteristics of voice/data traffic, number of traffic sources, etc).

When a single T-D curve is used, throughput is the driver. For a given throughput level, all packets/messages are delayed by a given amount. All other variables have been averaged out (or eliminated). Since packets are only delayed, never lost, no packet losses can be simulated.

7.2 ***Family of T-D Curves***

A family of throughput/delay curves is the first level of refinement of the T-D curves approach. With this approach, one can eliminate a strong dependence on a given variable. For example, if message size were a critical parameter, one could produce a family of curves where each curve is valid for a (narrow) range of message sizes (see Figure 4).

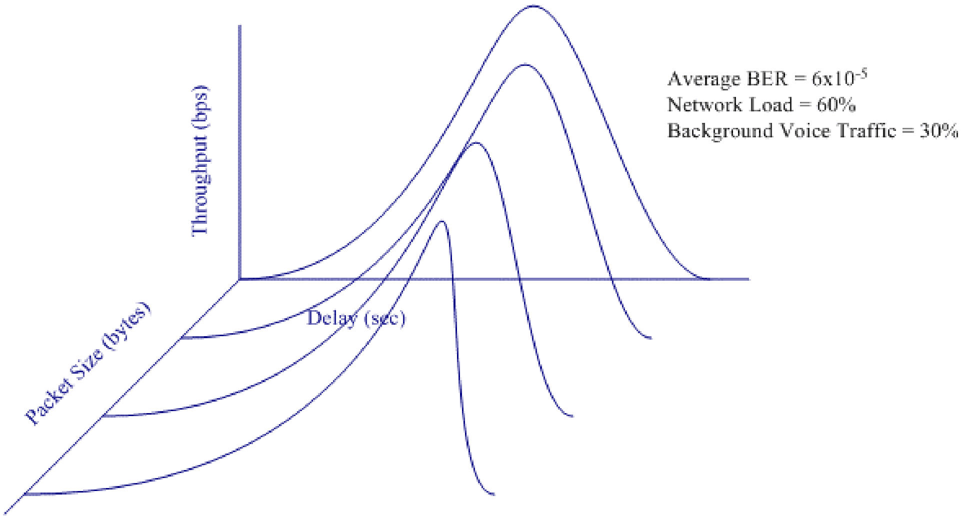

Figure 4. Illustration of a Family of Throughput/Delay Curves

A further extension is to have each T-D curve characterized by more than one parameter. However, the difficulty in such a case is that the size of the family grows quite rapidly with the number of parameters. Each T-D curve provides a statistical characterization of the channel for a given set of parameters and a given range of values of these parameters.

As before, each T-D curve should be used within the range of values of system parameters for which it is valid. As is the case for the single T-D curve approach, if the number of nodes in the network and/or the network load varies, new T-D curves should be produced.

When a family of T-D curves is used, first a specific (set of) parameter(s) values are used to select which T-D curve to use, and then throughput is the driver for this set of values. For a given throughput level, all packets/messages are delayed by a given amount.

7.3 ***Markov Process***

Markov models are used extensively in speech processing, neural networks and other fields. However, their use for communications applications has developed rather slowly. In the communication field, they were first brought to light by their use in the derivation of the capacity of a burst-noise channel [Gilbert, 1960]. In the 1980’s, they were used quite successfully in studies of HF and satellite channels. Digital error injectors were often based on an underlying Markov process. More recently, they have been used to model (mobile) wireless channels such as IEEE 802.11 and GSM [Konrad *et al.*, 2001; Gomez and Campbell, 2000; Golmie and Mouveaux, 2000; Balakrishnan and Katz, 1998] and even VHF CNR networks [Roman, 1991]. A good summary of models for channels with memory is presented in [Kanal and Sastry, 1978].

The traditional Markov process approach to error modeling is to create a Gilbert-Elliot model [Gilbert, 1960; Elliot, 1963] (i.e., a two state discrete Markov chain) based upon collected network traffic traces. Using such a model, one can dynamically generate synthetic network traces for the network under study and use the traces to simulate the performance of existing and new network protocols and applications.

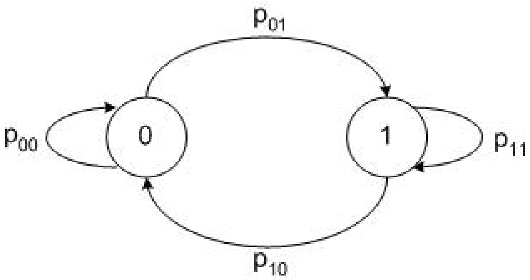

Figure 5. Gilbert-Elliot Channel Model

The Gilbert-Elliott model is characterized by a two-state *(N* = 2) Markov chain $\{C_n\}_{n\geq 0}$, where C_n is a random variable associated with the state of the channel at time instant *n*, with state transition diagram as shown in Figure 5. Under the Gilbert-Elliott model, the physical channel assumes one of two states; one state is associated with a low probability of bit error (state 0 or *good* state), while the other state is associated with a high probability of bit error (state 1 or *bad* state), each having an associated error probability $P_e(k)$, $k = 0, 1$ and $P_e(0) << P_e(1)$. The state transition probabilities p_{ij} can be derived from the experimental channel data.

Using a Markov Process approach, one can reduce significantly the number of assumptions that were necessary with the T-D approach. The only piece of information needed to characterize the Markov model is the error statistics of the link(s). This is used in the derivation of values for the state transition probabilities. Assumptions regarding message/packet sizes, frequency of transmission, network load, number of network nodes, etc. are not needed as the process is applied to each message/packet individually. The Markov process approach results in much finer granularity of the RCS and a higher degree of fidelity/realism in simulation of the radio channels.

A corollary is that the use of a Markov process introduces an element of randomness in the simulator. This is due to the fact that one cannot, in theory, predict what is going to happen to a bit/packet/message until it has gone through the Markov process. However, results are exactly reproducible due to the fact that, for a given random seed and probability function, a computer always produces the same outcome.

7.4 ***Comparison of the Approaches***

7.4.1 ***Stationarity***

All three approaches assume that the channel is stationary. Although it is known that the wireless channel is often not stationary, violating this condition is not as catastrophic as it may seem because (a) for much of the time the channel will be stationary, and (b) the test bed experiments are concerned with relative, not absolute results, i.e. one wants to measure the effects of changes in information management schemes.

7.4.2 ***Network and Traffic Model Assumptions***

The single T-D curve approach makes the most assumptions and averages the results over the largest set of parameters. It is significantly less precise than the other approaches.

The family of T-D curves approach groups values of one or a set of parameters into ranges that are used to characterize each T-D curve. It is more precise than the single T-D curve approach.

The Markov process approach does not require any *a priori* assumptions about the traffic model except possibly for the voice/data mix. From a network point of view, the distribution of traffic sources and sinks does not need to be known *a priori* either. It is therefore the most precise of the three and introduces a higher level of fidelity (realism).

7.4.3 ***Network Topology Assumption***

Strictly speaking, a Markov process should be associated with each link between nodes since each of them will in practice have different error statistics. This is a result of the fact that each link might be of different length (i.e. signal-noise ratio), some stations might be hidden, there might be different topography between stations, etc. Using a single Markov process is equivalent to saying that each link between pairs of stations has identical communication characteristics[3]. These same considerations apply to T-D approaches.

Whatever approach is selected for the test bed, it is only if the characterization is on a link basis, i.e., a station pair, that it will be possible to "simulate" these effects and thus to have greater variability in the consistency of the databases. It is far more feasible to implement characterization on a link basis with a Markov process than it is with a family of TD curves. This characterization will be a much more accurate reflection of reality.

7.4.4 ***Reproducibility of the Results***

The T-D curve approaches can be considered deterministic approaches. The Markov process is a stochastic approach since it involves state transition probabilities between and within states of the model. However, as noted above, for a given random seed, computers yield the same outcome to a probabilistic event. All approaches produce results that are strictly reproducible.

8. **Conclusions**

Quantitative assessment of the impact of information management techniques applied over tactical radio networks, using the test bed concept discussed in this paper, requires that experimental conditions and results be highly reproducible and that the sequence of battlefield events be human-selectable. These characteristics are necessary to allow isolation of the effects of the information management techniques being tested.

Use of a deterministic battlefield model based on a scripted scenario will provide the required reproducibility and full control over event sequencing. A stochastic battlefield model, as provided

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[3] The RCS could be upgraded at a later date to take such effects into account (e.g. take into consideration geography) if Markov processes are used.

in computer simulation applications like JANUS and ModSAF, produces results that can be made strictly reproducible if the same random number seed can be employed. However, such a model will not provide full human control over scenario composition and event sequencing. A deterministic battlefield model offers clear advantages for the test bed studies.

All three approaches discussed in this paper for the test bed's communication channel model, whether deterministic or stochastic, will produce results that are strictly reproducible (provided that the same random number seed is employed, in the case of the stochastic approach). The selection of an approach to the communication channel model must be based on another criterion. This criterion is the model that exhibits the highest degree of fidelity (or realism) to the real channel behavior while at the same time remaining computationally efficient. The Markov process approach is clearly superior to the throughput/delay curve approaches in this regard. The approach offers a much finer granularity and is a much more accurate model of the communications system. The Markov process approach to the communication channel model offers a clear advantage for the test bed studies.

9. **References**

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