Model-based Measures for Over-the-horizon Targeting with Improved Sensor-to-shooter Timeliness

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Abstract

Data collected during a series of experiments planned by an AUS-CAN-NZ-UK-US working group that was mandated to develop "Guidelines for Maritime Information Management" provide important insights into the development of future systems and the improvement of current ones. In previous studies we reported on model-based-measures (MBMs) designed to link systems performance changes to mission effectiveness, focusing on the capabilities of afloat-command information systems to support over-the-horizon targeting (OTH-T). Using knowledge of the architectures, the planned information flow changes, the tactical information required for OTH-T, the data collection plans used during the experiments and the ground truth for a posteriori assessments, we investigate here the potential gain in OTH-T effectiveness that results from improvements in sensor-to-shooter information flow and timeliness. This gain may be independent of the particular implementation of system changes but should depend strongly on the ability of a specific change to deliver timely, precise and appropriate information to the shooter. Changes could depend on independent dedicated asset and systems, as will be investigated in one of the Joint Warrior Interoperability Demonstrations (JWID) planned for 1999. Alternatively they could result from the integration of the sensor-to-shooter concept within the current architecture using a modified standard operating procedure (SOP) and appropriate middleware. The current architecture combines the Force Over-the-horizon Track Coordinator (FOTC), the Allied Command Information Exchange System (ACIXS) and the Global Command and Control System (GCCS). Both possible implementation strategies could offer information with similar quality to the end user; consequently they may improve mission effectiveness to the same degree.

1. Introduction

Improving over-the-horizon targeting (OTH-T) in a cost-effective fashion requires an appropriate combination of changes that range from optimizing resource deployment to generating productive decision plans. Optimal resource deployment considers assets used for appropriate surveillance and for the positioning of weapon launchers: ships, for example. Generating productive decision plans requires and includes transforming data into information, developing and sharing knowledge, understanding the situation and the intent of the opponent, devising and sharing realizable plans and executing them in a manner consistent with their time-dependent probability of success.

The depth and breadth of all the issues related to improving OTH-T are beyond the limited resources of the author's project and of this paper. However, findings based on simulated and live military exercises using model-based measures (MBMs) open new avenues in assessing the value of systems changes to improve mission effectiveness. This paper addresses the impact of improved sensor-to-shooter timeliness on OTH-T effectiveness, an issue that may have an impact on the R&D plans of the Canadian Navy for future cooperative engagements, both with national joint assets and during coalition or joint operations.

In this document we identify the approach, the source of experimental data, the current architecture, proposed changes, measures of success, possible implementation changes, potential gains, samples of progress in MBMs and conclusions and recommendations.

2. Approach

The evaluation of effect of communications, command, control and information system (C3IS) improvements or changes on military operations or on mission effectiveness can be conducted through characterizations of system performance and information quality known as measures of performance (MOPs). These results fall short of demonstrating the impact of C3IS improvements or changes on the actual capability to conduct successful operations or on mission effectiveness, defined here as measures of effectiveness (MOEs). Only by relating information quality and system MOPs to decision and mission MOEs in a causal manner can one establish the value of the wide-area tactical information a commander uses to plan operations and make decisions. This relationship fulfills an essential analysis requirement for comparing the effects of changes in wide-area picture (WAP) systems and procedures on mission effectiveness and can also lead to cost-effective planning of both system development and military operations.

In this context, the Defence Research Establishment Valcartier (DREV) has developed specific MBMs to determine the effect of information quality and system performance on mission effectiveness. The MBMs assess the value of the information made available to a commander by examining each tactical report of track data that meets a particular set of engagement conditions. Location, systems and temporal data are used to establish the engagement parameters and scenarios. Outcomes subsequent to decisions are assessed using both decision-process model definitions and algorithms that include hit-probability calculations, as well as ground-truth information about actual target locations (possible because this is a post-exercise analysis). Areas-of-uncertainty (AOUs) are used to represent the intrinsic level of uncertainty of missile-interception areas, of ground-truth data and of the information presented by C3ISs to commanders. The measures assign reward values that take into account the allegiances of contacts in the interception area and a utility cost for firing a missile.

Using MBMs as a yardstick based on OTH-T effectiveness, various potential changes to the architecture used in Coalition exercises for improving the timeliness and accuracy of the information made available to the decision makers at time of decision (a MOP) are assessed in terms of their impact on OTH-T potential success rates (a MOE). We distinguish between changes to information exchange procedures and the architecture/hardware used for information processing. In this paper information processing includes sensor data processing, data fusion, situation assessment, weapon pairing, action planning and other deliberative processes that take place before sending the engagement data to the shooter. The information exchange concerns the geographical distribution of the required engagement data from an information-processing node to a shooter.

3. Experimental Data

To study WAP systems, the AUS-CAN-NZ-UK-US[1] C3 (command, control and communications) [1, 2] defined a work program and set up an ad-hoc working group to investigate the management of organic and non-organic information in a maritime environment (MONIME). MONIME was mandated to conduct a series of experiments to collect sufficient data for WAP systems analyses, characterization and requirements definition. Experimental data include the 1993 Tactical Information Management Simulation (TIMSIM ’93), the Rim of the Pacific live exercises 1994 and 1996 (RIMPAC ’94 and RIMPAC ’96) and the second 1995 Maritime Command Operational Training Exercise held along the Pacific Coast (MARCOT ’95-2) data. Results and recommendations from this series of experiments form the basis of the AUS-CAN-NZ-UK-US C3 Organization’s “Handbook 5 (HB5), Guidelines for Maritime Information Management”:

[1] Australia, Canada, New Zealand, United Kingdom and United States, committees for operations interoperability.

guidelines to be used in the procurement of national C3I WAP-based systems for the compilation and sharing of accurate WAPs [3]. This document is referenced in "The Major NATO Commanders CONOPS[2] for Information Management" 1998.

4. The Tactical Information Architecture Used in the Coalition Operations Observed

The architecture used in the RIMPAC exercises sampled is based on a central node that processes data from local and remote sources or sensors (including space-based assets). The Force Over-the-horizon Track Coordinator (FOTC) requires several Global Command and Control Systems (GCCSs) and is a man-intensive information processing and management function usually assigned to a suitably equipped ship, e.g., a carrier vehicle (CV). The FOTC fuses and compiles the tactical picture. Procedures allow the data, mainly track information, to be broadcast periodically[3] by satellite or radio, the Allied Command Information Exchange System (ACIXS)[4], for example. High-interest tracks can be sent over narrow bandwidth radio channels for participating units not on ACIXS. Participating units use GCCS in conjunction with their C3IS for planning and operations.

4.1 Tactical Information Used for the Tests

MBMs were tested for the surface segment of a wide-area naval tactical picture of warships sailing within their areas of operational interest (AOIs) that report on a variety of contacts. However, the information-exchange traffic included all types of tracks (e.g., air and submarine) and other systems and operations information required, but our MBMs only addressed the value of the information regarding Over-the-Horizon Targeting (OTH-T) against hostile ships. The ships of the surface tracks can be classified according to their perceived or reported allegiance as friendly (F), hostile (H), neutral (N) or unknown (U), a subset of NATO-defined allegiances [3-5]. Friendly and hostile ships are military vessels of the forces in conflict. Usually we refer to friendly ships as the "blue" force and to hostile ones as the "orange" or "red" force. Neutral contacts are generally merchant ships, liners or other vessels extraneous to the conflict. The unknown allegiance category indicates a lack of information about a contact. A perfect reporting system with all the appropriate information would not need this category.

4.1.1 Ground Truth

Different ships or groups of ships may and usually will have different tactical pictures of a given area at any given time, despite the ultimate goal of sharing the same picture at all times by all units of a battle force. With current systems, the tactical picture available to commanders may be incomplete, erroneous and cluttered with duplicated information. There is, of course, only one real wide-area naval situation at any given time. We refer to this situation as the ground truth (GT). GT information consists of the identification, allegiance and location at any given time[5] of every ship in the area to be controlled, over the period of time considered. In post exercise analyses we use GT, though it may not be perfect [6]. The only GT allegiances used are F, H and N.

4.2 Operations

For our MBM purposes, an OTH-T engagement situation occurs every time an armed ship from the blue force has knowledge of the presence of an enemy ship (orange force) within range of the ship's weapons. This knowledge is acquired through surveillance operations whose sources can be

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[2] Concept of Operations

[3] Periodic update times observed in our data include 20, 15 and 10 min.

[4] The OTCIXS, Officer in Tactical Command Information Exchange System, or ACIXS, is a communications systems that uses satellite technologies at data rates ranging from 2 400 to 9 400 kb/s. TADIXS, Tactical Data Information Exchange System, is the real system (UHF SATCOM data link) and OTCIXS or ACIXS is a concept.

[5] In practice, the GT data are listed according to a discrete time variable with short steps (set to 1 min in our tests).

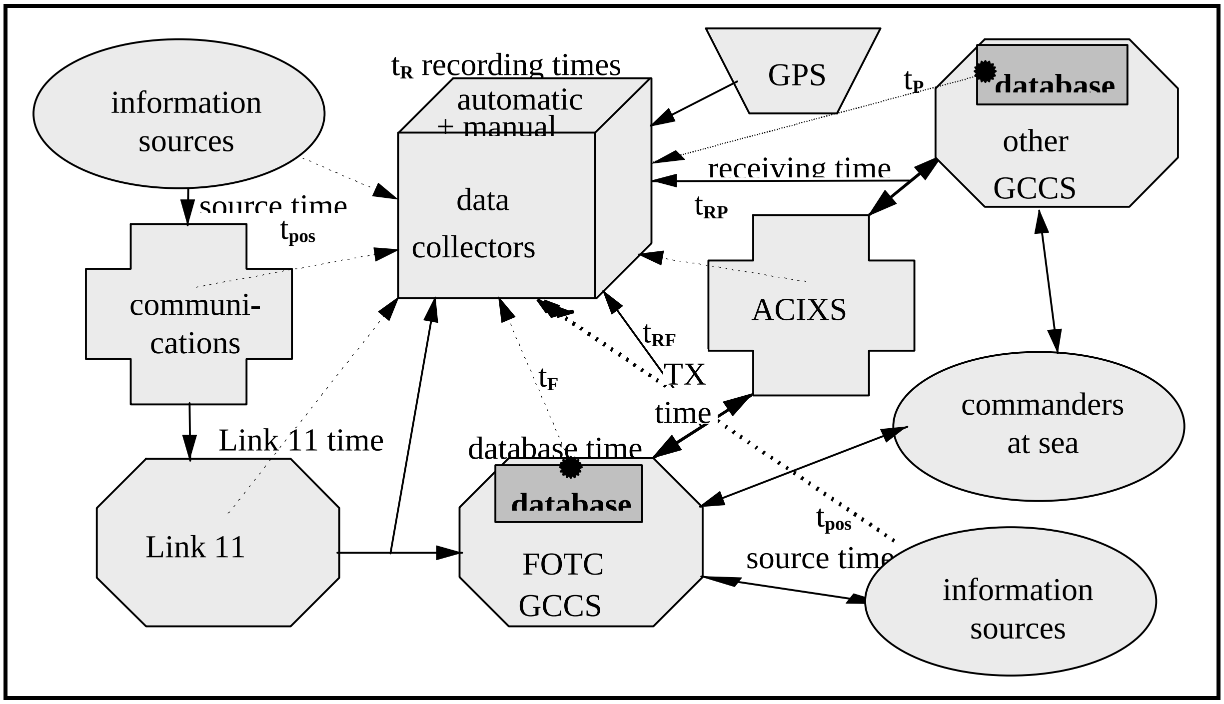

Figure 1. Typical coalition information exchange architecture and data collection for a live exercise[6]

within (organic information) or outside (non-organic) a blue force commander's assets and organization. Information may also be based on intelligence reports. We assume that the commander follows appropriate procedures and that the target is located within the physical limits of the systems (mainly the weapons) and that it can be engaged according to the applicable rules of engagement (ROEs). Then an engagement situation occurs each time a blue force C3IS receives an information report on a presumably hostile contact. For MBMs, hostility depends on the identification/allegiance indicated in the information report.

Tactical information about a ship contains its identification (class-name), its position and, at least eventually, other information such as course, speed and allegiance. Each occurrence of such a data combination is referred to as an information report on a contact. Each such report recorded during an experiment (an exercise or a simulation) also holds two time values: the "position time" and the "report time." The position time t_{pos} is the time at which the information was acquired by the sensor (sensor time). The report time t_r indicates when the information was made available to its recipient's database (WAP database time).

4.3 Experimental Setup

The report time t_r must be estimated, since available instrumentation captures only the time (the recording time of Figure 1, t_R) at which the report is observed during its transition out of the compilation node (e.g., the FOTC) or into a recipient node. The information in a report does not change (except for the current time) until a new report for a given track or contact has been correctly[7] received and has been inserted into a C3IS database, or more specifically a GCCS[8] data-

[6] Not defined in the text: Global Positioning System (GPS).

[7] Correctly received report: A report processed by the C3IS node and added to the database for this track. Reports that should have been correctly received but did not appear in the database are not considered: MBMs are limited to what the commander can see.

[8] GCCS-M or JMCIS, Joint Maritime Command Information System and/or Strategy (US); it includes NTCS-A and interfaces.

base: R(t) = constant for $t \in [t_{pos}$, time of a new report for that track[[9]. Only the associated time and identification (i.e., the unit identifier) of the database change.

Assuming no processing or transmission delays, at time t_{pos} we assess the goodness of the sensor data for a decision (sensor baseline). After a delay ($t_r - t_{pos}$), i.e., at time t_r, we assess another MBM as soon as a report enters a GCCS database. A report tells us where to apply the MBM and time tells us when in the GT file.

In Figure 1, solid lines to the data collectors represent collected data, and dotted lines indicate the desired data that must be estimated from available data. The FOTC is at the compilation node, and the time $t_{\mathbf{F}}$ of Figure 1 is the FOTC time estimated by the transmission time $t_{\mathbf{RF}}$ ($t_{\mathbf{RF}} > t_{\mathbf{F}}$). As soon as an information item has been processed by the FOTC staff and GCCSs, it is stored in the database. Then it is queued to outgoing message lists as for the FOTC broadcast or another information service until the next transmission opportunity. The time when a report is received from another participating GCCS unit is referred to as the participant time[10] or $t_{\mathbf{P}}$ in Figure 1. All this happens in real time, while sampling the process of developing and sharing a common WAP.

In practice, the information reports received by a ship are manually or automatically entered into an input queue, not directly into the database, and the report time thus represents the time at which this operation was performed, without regard for delays due to instrumentation. So there are two recording times, $t_{\mathbf{RF}}$ and $t_{\mathbf{RP}}$: $t_{\mathbf{RF}}$ for the FOTC and $t_{\mathbf{RP}}$ for the participant receiving time, with $t_{\mathbf{F}} < t_{\mathbf{RF}} < t_{\mathbf{RP}} < t_{\mathbf{P}}$. For our purposes, we consider that the commander of a ship has knowledge of an incoming contact information report at t_r , which we approximate with $t_{\mathbf{RF}}$ and $t_{\mathbf{RP}}$ depending on the measure required. This is supported by the typical values of t_r and instrumentation accuracy of the "recording time" presented in [6-9]. t_{pos} is the same for a given report independently of the database sampled, and t_r depends on the information system architecture used in the exercise (in our example the FOTC or one of the participants).

4.4 Areas of Uncertainty

The positional information in WAP systems is uncertain for several reasons. For example, any sensor that estimates the location and identification of an object it has detected does so with finite resolution. One aspect of its resolution, the positional accuracy, leads to an AOU around the estimated location. In some systems this contact AOU is provided by the source of data, but since AOUs are not yet systematically provided for in all the contact reports subjected to our analysis we impose an alternative in our model that is described later. There are also other types of AOUs that naturally arise in physical systems.

The data collected during military exercises may come from different information systems [3, 10, 11]. The instrumentation may transform these data, and the data are usually tagged with time stamps and with the identification of the originating system. For position information, Link 16 uses the World Geodetic System-72, WGS-72. Link 11 uses a data-link reference point (DLRP) and a Cartesian representation relative to the DLRP in "data miles," dmi, defined to be 6,000 ft (1,828.8 m). GCCS uses WGS-84 with distances in international-nautical miles, nmi (1,852 m) or users may select km instead especially for air (nmi), land (statute mile, 1,609.3 m) and maritime (nmi) distances.

4.5 Time of Engagement Opportunity

An engagement situation occurs whenever the commander of an armed blue ship receives an information report on a presumed hostile contact. This report holds a position time t_{pos} and a report

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[9] Brackets opened toward the outside mean that the exact value is excluded of the range of the variable, e.g., $t \in [t_{pos}$, time of a new report for that track[includes t_0 but excludes the new report time. Otherwise double accounting of data would occur.

[10] Note that $t_{\mathbf{P}}$ for the participating GCCS unit time is larger than t_{pos} , the "position time" from the sensor, and larger than $t_{\mathbf{F}}$ due to the delays required to process and transmit the information.

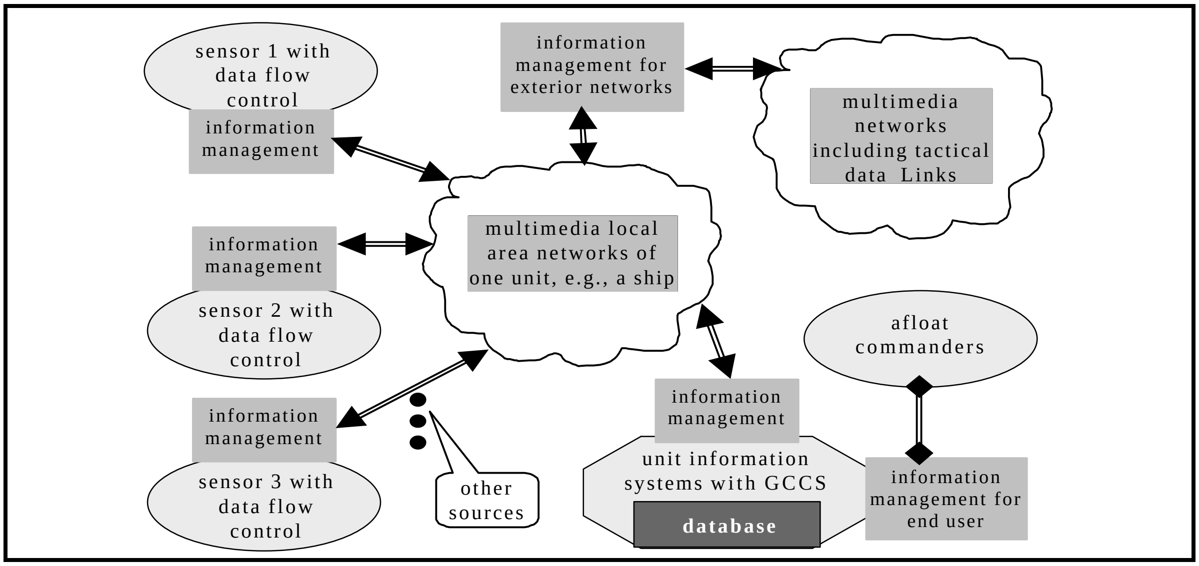

Figure 2. Typical information management required at a mobile unit level, a ship

time t_r, with $t_{pos} < t_r$. The models may use either of these two time values as the actual time of engagement opportunity, i.e., the time at which an engagement may take place (or might have occurred). Of course, in reality, an engagement decision cannot be taken before the existence of the information report is known. However, allowing the selection of different times of engagement in the models yields essential measures for estimating the impact of systems changes on mission effectiveness.

The baseline assessment models used may be viewed as “optimal” since they are equivalent to assuming that information reports are available instantaneously, when they are generated by sensors/sources (i.e., position time = report time = time of engagement opportunity). These models deliver the maximum usefulness value of the available information that can be provided to a commander. This value is the source or sensor baseline that can be used to evaluate the impact of systems architecture changes on mission effectiveness.

The delay models are “time degraded” models where the target information has not been updated since position time (i.e., position time < report time = time of engagement opportunity)[11]. Time degradation of the information represents system limitations that are assumed to be sub-optimal.

Actual engagement decisions are few in live or realistic exercises, so the conclusions drawn from their outcomes have very little, if any, statistical significance. In contrast, applying the models as we did over the experimental data yields samples of sizes approximately a hundredfold larger, which reinforces the statistical soundness of inferences made.

4.6 Some Information Management Required in Coalition Operations

There are a large variety of information management (IM) concepts required for developing and sharing the information and knowledge that evolve during military operations that would improve and maintain mission effectiveness and information dominance [12]. As shown in Figure 2, one unit may require the following IM capabilities: sensors with data-flow controls that match mission requirements (sensor cueing, data fusion rate, users’ requirements, cooperation between applications), local area connections with some middleware that optimizes information exchange between remote applications (systems or software objects), end-user systems with information selection

[11] The position time or sensor detection time is earlier than the report time. We set the time of an engagement to the report time so as to measure the effect of data aging on the result of the engagement.

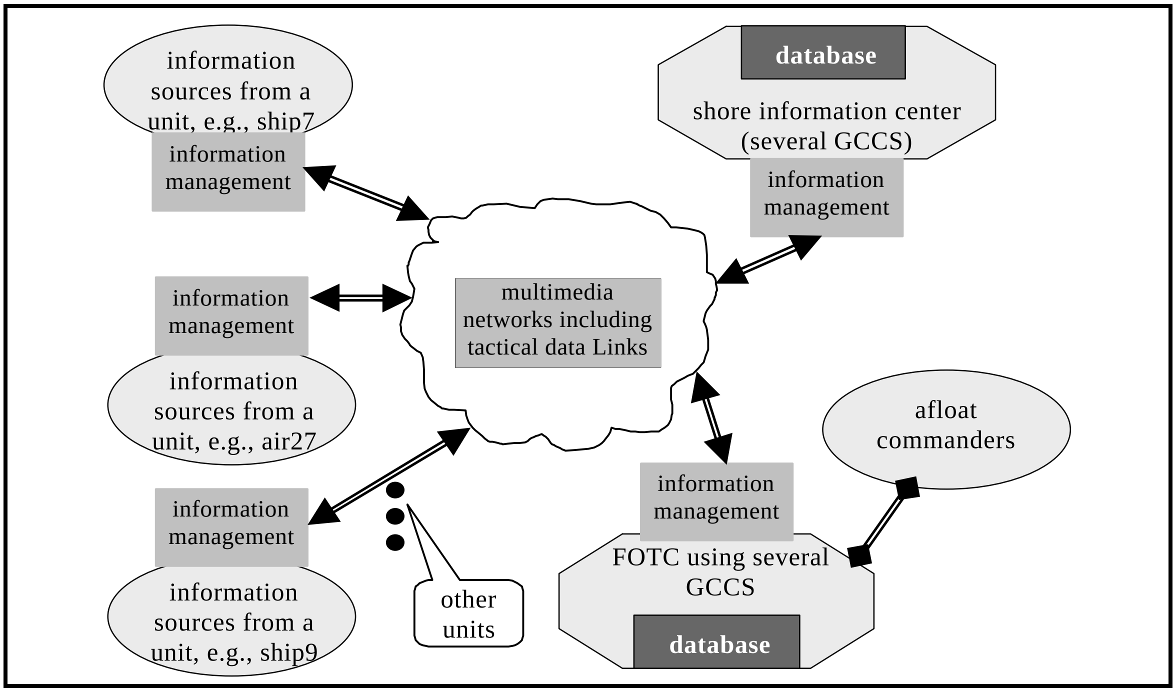

Figure 3. Information management for better information sharing over multimedia networks for a force

and presentation according to some rules (AOIs, types of behavior of contacts), and exterior connections with some middleware for optimizing the effectiveness in sharing the developed information and knowledge available from all participating units. The latter is the subject of the remainder of this document.

Information management for better information sharing over multimedia networks, Figure 3, requires exterior connections via some middleware to optimize the sharing of all the information and knowledge developed across all the participating units.

Results from previous studies indicate that the overriding need is for better exploitation of existing sensor and source data through improvements to WAP systems, concepts and procedures at tactical information management nodes or in distributed versions of these systems.

5. Middleware

"Middleware services are sets of distributable software services that exist between the application and the operating system and the network services on a system node on the network. Whether the applications are called 'distributed,' 'networked,' or 'client/server' doesn't matter. In all those cases, middleware services provide a simpler and more functional set of APIs than the operating system and network services to allow an application to[12]:

1. locate transparently across the network, and interact with another application or service (e.g., data, print);
2. be independent from network services;
3. be reliable and available; and
4. scale up in capacity without losing function."

State-of-the art computing technologies and concepts for distributed applications address some of these problems with a structured approach, yet in a highly dynamic environment. A subset of the

[12] www.datamation.com issues by Richard Schreiber, April 1995.

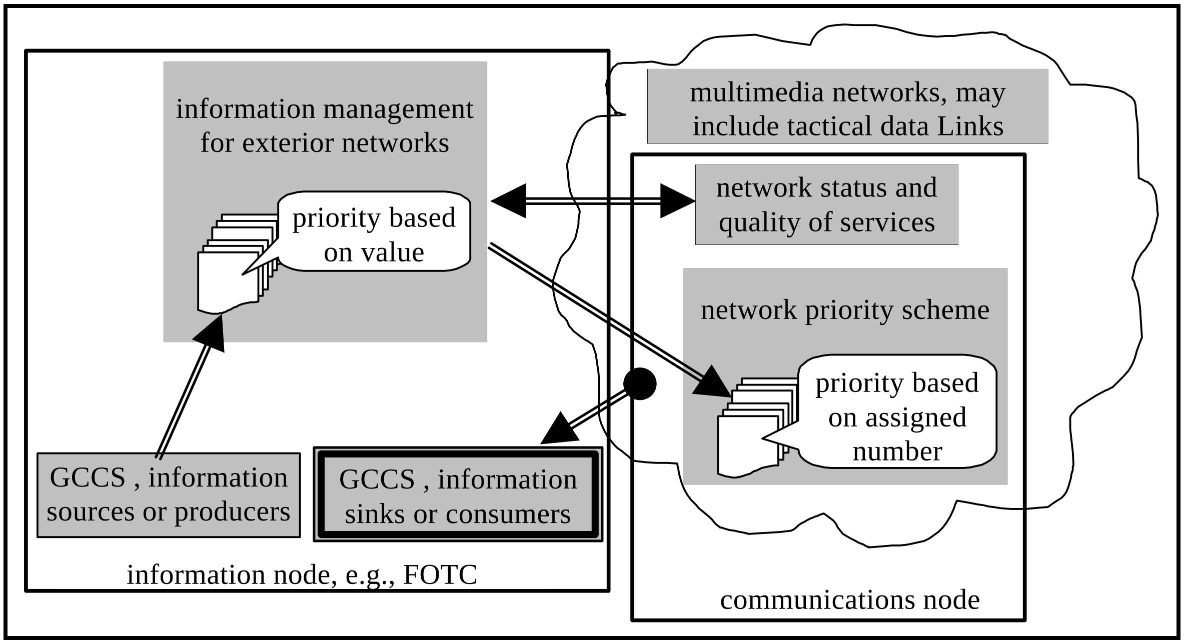

Figure 4. Cooperation between multimedia networks and the information node

required functions related to our experiments is illustrated in Figure 4. Several approaches have been proposed and the author has identified three options: Object Linking and Embedding (OLE) by Microsoft for Windows applications, OpenDoc by the Component Integration Laboratories (CI Labs) for various platforms, and Common Object Request Broker Architecture (CORBA) by the Object Management Group (OMG). We select the last one, CORBA, for its potential to fulfill many of the requirements for better quasi-real time tactical information sharing and distributed knowledge building (the development of knowledge in a collaborative geographically distributed process). Figure 5 shows CORBA functions that encompass those of Figure 4 for our experiments. It is understood that a lean version of CORBA is required when the distribution is over low-capacity radio channels. However, the creation of an alternate replicate of the information within the application node for managing the outgoing information queue as in Figure 4 may help in better using these low-bandwidth networks and consequently will improve responsiveness to users.

For example, some CORBA implementations include components for message queuing, transaction monitoring and processing, and an open-software concept for distributed computing. Such capabilities seem to support the model described here and in previous works [3, 13, 14]. Future CORBA implementations may include all that is necessary to compute priority according to the application needs or quality of object (QuO) requirements and use the current status of the network in terms of delays and quality of services (QoS) to manage information exchange efficiently. Here we assume that the local computer processing time is negligible compared to the transmission time when using low-capacity radio channels. Another important factor that slows down information processing and sharing is the man in the loop, when manual interventions are required as in situation assessment, but this aspect can be addressed separately and is outside the scope of this paper. We account for its effects, however, in our computation of the potential gain of architecture changes, later in this report.

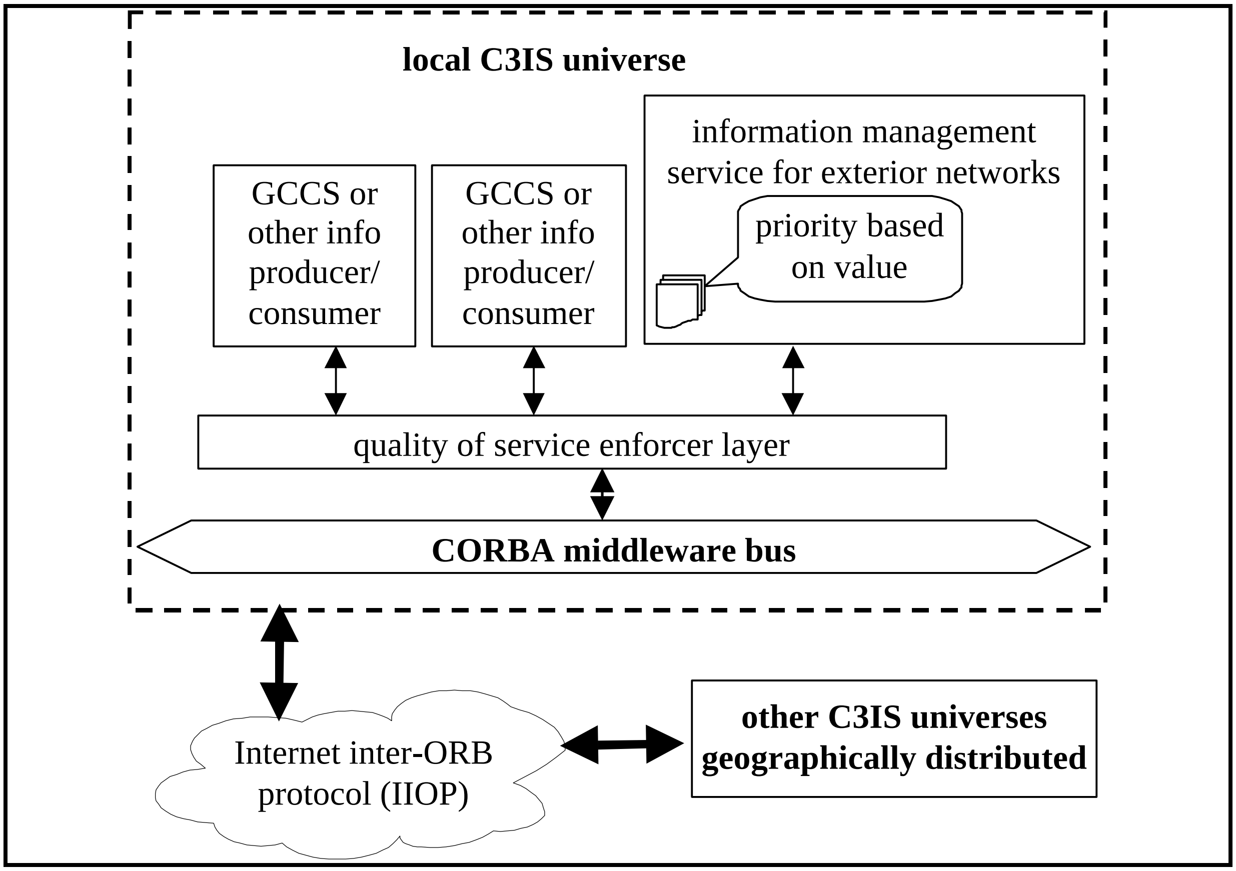

Figure 5. CORBA interpretation of our requirements for improving information sharing and cooperative engagement capability[13]

6. Possible GCCS Tests for Assessing Improvement to Information Sharing

A short examination of the GCCS transmission queue management abilities (outgoing messages) for broadcast in the FOTC function and other information-forwarding functions reveals a variety of IM possibilities that may improve the value of the shared information for missions.

Outgoing messages may be selected for a given geographical area that matches the operational AOIs of the deployed units. Different transmitting strategies may be defined with their own outgoing message queues. During RIMPAC exercises, ACIXS and high-interest track (HIT) broadcasts were used. It is possible to use the time currency of the reports in order to select data that is older or younger than a certain date and to implement a first-in/first-out (FIFO) or a last-in/first-out (LIFO) strategy.

Some IM heuristics that improve tactical information sharing may be defined from the results of HB5 and the exploitation of the GCCS IM transmission abilities. However, schemes or information management heuristics that prioritize data to be sent based on its information value to a task or a mission cannot currently be implemented easily in the GCCS software. For more complicated schemes that identify data to be sent based on the significance of changes relative to thresholds defined for tasks and missions (e.g., attribute changes such as allegiance unknown to hostile, or new position beyond 2 nmi from a previously reported position) appropriate software improvements are needed. Some of the modifications required are closer to the application software of the

[13] Adapted from the material prepared by Éric Dorion at DREV.

information node, others are more in the middleware area. Should the middleware use an independent version of the sharable database to interact with other units and with the local information databases of its unit?

6.1 Priority Based on Information Value to Missions

In Coalition operations a large variety of information needs to be exchanged at significantly different quality-of-service levels. If one assumes that some kind of priority scheme can govern the radio-communications asset to be used (exploiting the NATO Communication System Network Interoperability (CSNI) project results), one needs to assess the value and timeliness of the data to be exchanged according to requirements for the successful accomplishment of each addressee's tasks.

Assigning priority to messages, packets or cells in terms of task or mission effectiveness requires the extraction of the information they contain, to find what each piece of data means for the end user. Using knowledge about the missions and tasks to be accomplished and from established time and location value attributes for information per task, the value of the data and related time-line requirements are assessed. Then, through an appropriate combination of factors in a utility function, the current priority of the data can be computed from the time-dependent value of the information. The value of certain data may depend on a combination of information from other data sent simultaneously; the value is conditional on the ability to send the combined data within a given time interval. All time-dependent pieces of information stacked in such priority queues (i.e., the priority-based-on-value queue of Figure 4, not the queue on the network side) must be reassessed prior to a transmission opportunity.

For example, a one-hour moving time window for a complete database update combined with a one-minute partial synchronization for priority information (not "real time," but improved timeliness) may impact OTH-T for surface warfare and significantly increase the mission success rate. Then, to update the distributed databases and to improve partial synchronization, new information is sent as soon as possible using a priority scheme based on the value of the new information relative to that of the backlog information. Backlog information is required for the coherence of the one-hour database imposed by some mission effectiveness measure. Consequently, we are trading bandwidth, manpower and system resources used to share high-value timely information that may result in higher mission effectiveness against a small decrease in database synchronization (by delaying the exchange of data with low information value) and coherence, which does not substantially decrease the success of the overall combination of tasks and missions conducted over the various AOIs. It is not true optimization, but it is a solution that can be computed in a finite time using only local and current information and knowledge available to a unit, including that accessible over the network.

6.2 A Simple Information Management Heuristic (IMH)

A simple yet efficient heuristic to improve the value of shared information might be to use two transmitting queues for the FOTC broadcast. One would be for outgoing messages that are the most current, say not older than one minute. The number falling in this category is small, permitting short broadcasts every minute that information is ready to be sent. This should improve database synchronization responsiveness and timeliness. The second queue, for outgoing messages older than 60 min, would be used to help maintain database coherence and to resynchronize when, for example, a new participant joins the net. Its use is spread over a moving time window so to avoid retransmission of the same data more than once every hour, since the large amount of data might saturate ACIXS. Limiting the geographical area of the reports to be sent would certainly help and would not affect the conduct of most missions. Using such IMH would allow a moving unit to adapt its database progressively from one FOTC area to the other, progressively impoverishing its database coherence with the former FOTC and enriching coherence and synchronization with its new FOTC. By the end of the move, the unit would be almost fully ready for its new assignments.

Our short review of GCCS documentation did not suggest that the current version used by the Canadian Navy[14] can easily implement IMH with transmission priority based on value of the messages to a mission, as computed by the utility function described in [13]. However, the proposed simple IMH can easily be implemented with the current GCCS software and hardware since it does not require the computation of the information value, a capability that is not yet implemented in GCCS.

6.3 Qualifying Track Information in Lieu of Coding

A statistic may provide insightful information about a set of observations without requiring an end user to examine all the data. Statistics, confidence levels, degrees of belief, value and quality of attributes are all candidates to decrease the amount of information to be examined before one reaches a conclusion or decides to act. It seems logical to postulate that they can be used to declutter WAPs. Currently there are standards that define such quality factors for tactical information. Position attributes have AOUs. Link-11 track reports have track quality numbers. Schemes for assigning these values were designed with sufficient care and understanding of operations and of the physical phenomena at play to offer a clear benefit to users who want to share the best possible tactical information using the least amount of data and radio-channel capacity. Since such steps improve the amount of useful information exchanged correctly over networks, one may consider them a form of coding based on the value of information, rather than the quantity of information bits exchanged.

Unfortunately, adherence to these standards and schemes is not mandatory, depriving the end users of such benefits. And to conserve channel capacity, unneeded information should be removed, e.g., if new information on a track is available before a transmission opportunity, any old versions should be deleted (in both one-minute and one-hour queues). Suitable statistical processing can take the multiple versions available into account and summarize the information to be used by the end user.

In the case of the proposed IMH, it can be argued that a one-hour broadcast interval is too long to support database coherence. On the other hand, if better adherence is imposed to schemes that assign quality factors to tactical information or track attributes, the global value of the part of the information common to all the participating databases in a geographical area will increase. Furthermore, the ability to send a short broadcast of timely information every minute by using the channel capacity saved by exchanging less data during one-hour global broadcasts should greatly improve database coherence and synchronization.

6.4 IMHs Expected Effectiveness Gain

The total loss in OTH-T mission effectiveness associated with the data aging between the sensor and the FOTC broadcast data was found to be 63% with the MBMs [15]. Consequently, 63% is the maximum achievable MBM improvement of WAP systems and procedures assuming instantaneous track management and information exchange. For this particular result the average time delay was around 20 min, for hostile tracks.

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[14] Joint Maritime Command Information System (JMCIS) Foreign Military Sale (FMS) 2.2.1, JMCIS FMS 2.2.1.

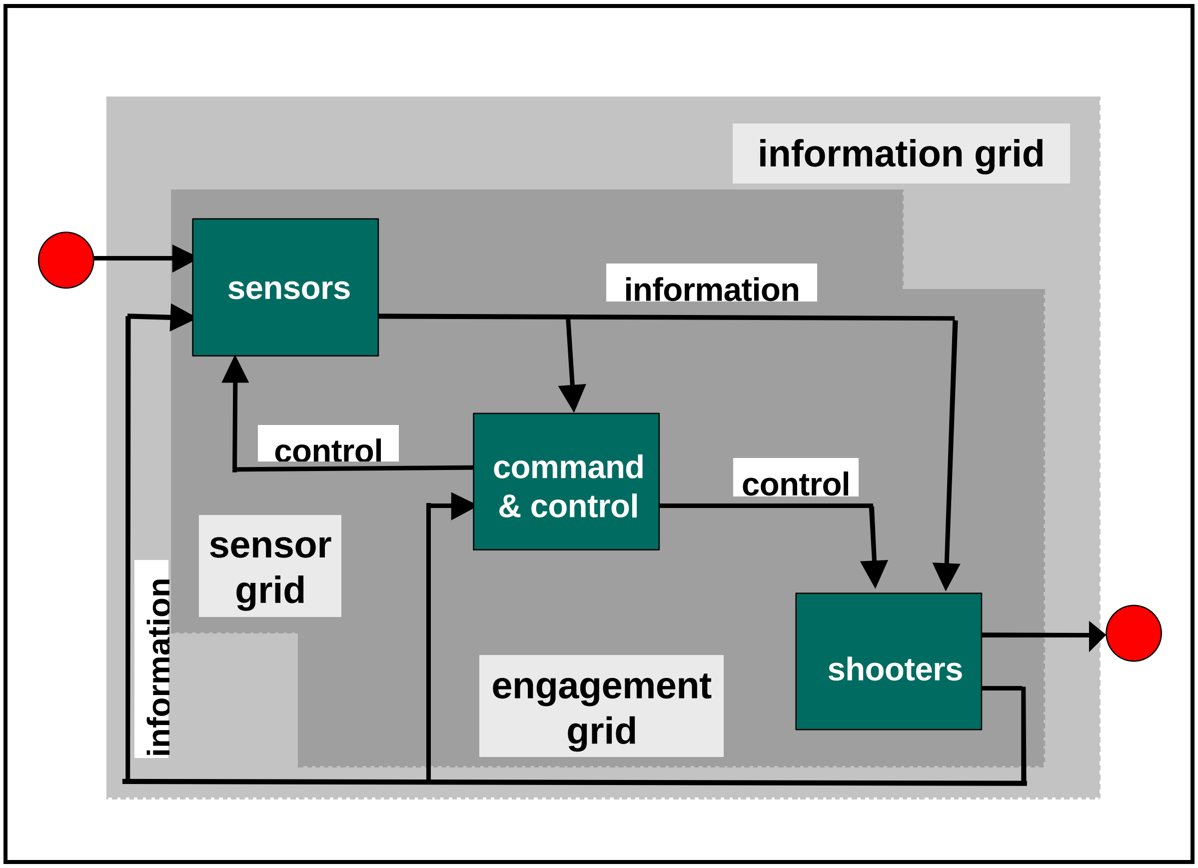

Figure 6. Typical information flow requires for improving cooperative engagement capability or the shooters-to-weapon timeliness[15]

Track data updates at the FOTC databases occur as they are produced by their respective track managers. Their frequency depends on a large variety of factors, including conflict status and tempo, current operations, surveillance-asset deployment, staff load, stress and training, and FOTC operations orders. Nevertheless, it is reasonable to assume that the staff cannot update all tracks manually at the same time; instead they will update them approximately uniformly over a period of time. If we assume a periodic broadcast from the FOTC every 15 min and track-data updates occurring uniformly during this period, certain updates may have occurred just at the beginning of his period and others just before the end. Over several broadcasts the mean delay should be about half the broadcast period, 7.5 min in this case.

The proposed naïve IMH imposes a one-minute short broadcast, or a mean delay of 0.5 min. Based on the 7.5 minute estimate of data aging imposed by a 15-minute FOTC broadcast procedure, the gain in time currency for this IMH should be approximately seven min. Though the effect of data aging on MBM might not be linear, a first approximation is to assume linearity, so one can expect the effectiveness gain of the IMH to be (7/20)•63%, **22%**. This is for the impact on OTH-T effectiveness based on the experimental data analyzed for hostile surface contacts reported by the FOTC.

[15] Adapted from the IC2_Wayhead presentation at the Canadian 1998 Information Management Seminar, slide title: “Network centric warfare, emerging logical model”.

7. Sensor-to-shooter Improvement and Cooperative Engagement

In some scenarios with weapons whose effective ranges are much in excess of own-ship sensor ranges, it is desirable to target using remote sensor information. Some missiles offer substantial target tracking and homing capabilities and in scenarios where the target can easily be identified by the missile seeker, such as a single ship in open-ocean area, precise targeting is not essential. However, a timely tactical picture is necessary to provide sufficient lead-time for high probability of mission success. On the other hand, some targets may be difficult to seek against their backgrounds, and it may be necessary to use alternate final homing methods that rely more on accurate inertial and navigation and accurate geodetic position estimated by intelligence and surveillance. If the target is mobile, continuous updates of the target position must to be provided during the flight of the missile. Other engagements may require intermediate accuracy in target positioning, relying on the seeker for the final intercept. In the dynamic cases, improved sensor-to-shooter timeliness is required to maintain a kill probability sufficiently high to make the engagement cost effective. Figure 6 shows this concept by a direct connection from the sensors to the shooters and Figure 7 illustrates an implementation of this as planned by the Canadian Navy for future ship upgrades.

In this context, the Canadian Navy is planning to improve information connectivity for national and coalition operations. Initially, exploiting the results of the NATO CSNI project would provide the connectivity required, but the cooperative engagement capability concept must also be implemented and integrated. Canadian research and development toward the Ship Integrated Information Management System (SIIMS) planned for 2010 should address these important issues. The system should encompass the integration of middleware strategies and the cooperative engagement concept as well as the optimization of information sharing as described in [3, 12, 13], where information value is used to prioritize the exchange of information.

7.1 Reported Time Lines for the Joint Attack Command and Control System (JACCS)

Reported Time Lines for JACCS in the JWID '99 demonstration plan (JW002), based on JWID '98 results, can be used as time references for improved C3IS timeliness. Values provided in seconds are converted to minutes: t_a acquisition and transmission delay 1.5 min, t_c compilation 1.3 min, t_J pairing (JACCS) 0.2 min and t_w weapon control 0.5 min for a t_t total from sensor to shooter of 3.5 min for the updates. However, it is likely that, for complex imagery that must be interpreted by trained operators and transformed into information and knowledge before a plan can be devised, the mean total delay would be around 7 min, with the 3.5-min figure possibly holding for updates.

7.2 Remote Sensing

Remote sensing assets such as the Canadian RADARSAT have demonstrated the ability to provide synthetic-aperture-radar or other imagery of surface and subsurface structures that intelligence staff can use to identify potential targets. Other images, along with geological and geolocational information, are then used to enhance the understanding of the sensed image and to describe accurately a potential target for a mission. Precision OTH-T is required for some missions, and missiles used in them may rely heavily on precise inertial navigation, with possible enhancement from other systems such as GPS.

Certain remote-sensing assets offer limited time-windows to view a given geographical area. The viewing opportunity is periodic and depends on the elliptic orbit of the satellite relative to the area to be observed. Furthermore, specific antenna and processing constraints and competition for service with other customer's requests further limit the availability, accuracy (because it depends on observation time and the amount of processing) and response time of such systems. On the other hand, for the intelligence purpose of better identifying and precisely locating underground structures, such delays are often acceptable because the potential target is not likely to move during the identification process, which might well be accomplished before the force asset is moved

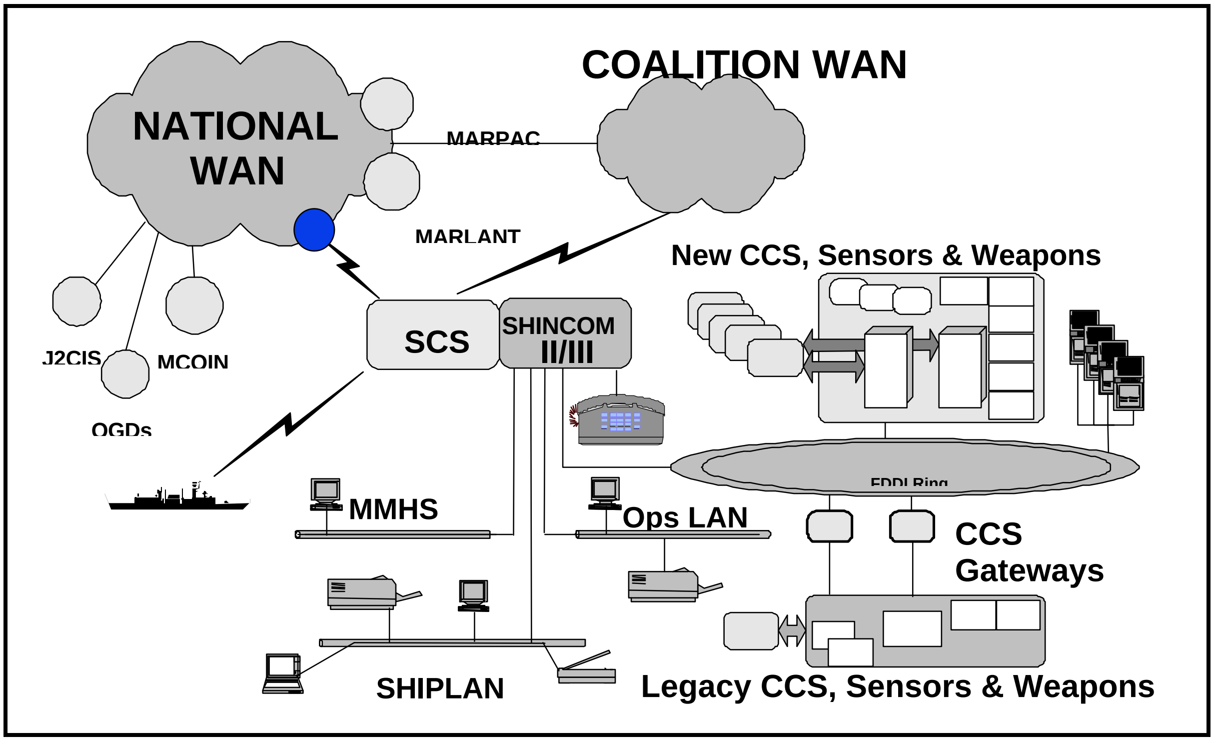

Figure 7. Planned ship communications system[16]

into weapon range of the potential target. Updates are more or less related to changes occurring in the vicinity of the AOI and can be sensed with alternate means (tactical sensors and visual contacts).

7.3 *Adapting Model-based Measures to Precision Targeting*

Precision targeting is not immune to error. Errors may be induced during the sensing and identification process, while interpreting and understanding the situation, within the definition of a plan (including weapon-target pairing) or its execution, or they may be due to environment changes that affect the probability of success or even the validity of the mission (the target is found to be of no value during the missile flight, for example). For these reasons the statistical models used in MBMs may advantageously be adapted to precision targeting. For this paper we did not adapt the weapon and target uncertainty area parameters for the case of precision targeting, but we assume that the results still have sufficient significance for our initial assessment of the value of the improved sensor-to-shooter architecture in terms of mission effectiveness because of the large potential impact that has been noted.

Current MBM implementations assume missiles with no attraction other than the statistical distribution defined over the weapon footprint uncertainty area. Although targets are assumed to be in the open ocean, the uncertainty areas assumed for them are useable in other environments as long as the assumed missile response is as described for the implemented MBMs. Future MBM studies will report on the effects of varying the uncertainty parameters. Also it is assumed that the target does not move significantly from the time the missile is fired to the interception time t_i (in fact, we set the flight time to zero). For more maneuverable targets or large t_i delay values, appropriate MBMs can be computed that account for the effective interception time.

[16] Adapted from The Naval Strategic Capital Program presented at the Canadian 1998 Information Management Seminar, slide title: “Ship Integrated Information Management System (SIIM)”.

7.4 Sensor-to-shooter Improvement in Terms of Expected OTH-T Effectiveness Gain

According to previous analyses and as reported here, the information processing time from the sensors to the FOTC database (after the situation assessment process) for collected data is the difference between 20 min and the 7.5 min required for the broadcast: 12.5 min. As indicated above, for new contact we may assume a delay of 7 min; that is, a timeliness improvement or a relative delay reduction of 5.5/12.5. The potential gain due to this MOP improvement can be associated with the remainder of the maximum total gain available, (12.5/20)•63%, or 39%. Then the potential gain for this MOP improvement is (5.5/12.5)•39% or 17%. For 3-minute updates the MOP improvement is 9/12.5 and the potential mission gain is 28%. In both cases we assume the current FOTC broadcast delay or an alternate architecture for managing, processing and distributing the data from the sensors to the shooter that adds a mean delay of 7.5 min.

If we assume that the information concept of the FOTC is modified as described above, these potential gains are slightly lower than optimum. First we have 7 min plus 0.5 min or an improvement of (12.5/20)•63%, or 39%. Second, we have 3 min plus 0.5 min or a gain of (16.5/20)•63%; that is, 52%.

If we assume that the information concept is as described for the JWID demonstration, these potential gains are slightly higher than with the integrated information concept with the FOTC. First we have 7 min or an improvement of (13/20)•63%; that is, 41%. Second, we have 3 min or a gain of (17/20)•63%; that is, 54%.

8. Architecture Changes

This section discusses the differences among the various architectures assessed in this paper.

8.1 Architecture Zero

This is our reference architecture (Figure 1); the one with which the experimental data described in Section 3 was collected. The maximum improvement possible to information processing and sharing from this reference to an hypothetical perfect information system in terms of the impact on OTH-T mission effectiveness for the hostile surface tactical picture was found to be 63%.

8.2 Architecture One

Architecture One (Figure 4) represents a procedure change proposed in a paper in preparation for MILCOM ’99 that addresses the impact on mission effectiveness of improving the FOTC broadcast timeliness MOP. Information processing in this architecture responds as in Architecture Zero. Results for Architecture Zero are used to show the relative effect of the postulated improvement on OTH-T mission effectiveness for the hostile surface tactical picture. The maximum relative impact on OTH-T of this MOP improvement on information sharing was found to be 22%.

8.3 Architecture Two

Architecture Two (Figure 1, but with improved FOTC information processing or separate hardware and software, as for the JWID demonstration) represents changing only the information processing procedures, not those involved in information sharing. Information sharing for this architecture is as in Architecture Zero; that is, the mean delay for the FOTC broadcast information exchange is 7.5 min. The maximum relative impact on OTH-T mission effectiveness for the hostile surface tactical picture on OTH-T achievable through this MOP improvement to information processing was found to be 17% for a 7-min initial mean delay and 28% for the 3-min updates (information generation time).

8.4 *Architecture Three*

Architecture Three (Figures 5–7, with improvements to FOTC broadcast and information processing and GCCS integrated into the ship command and control system) represents changes to both information processing and information sharing procedures. Information sharing in this architecture is similar to that in Architecture Zero, but the mean delay for the FOTC broadcast information exchange is 0.5 min. The maximum relative impact on OTH-T mission effectiveness for the hostile surface tactical picture on OTH-T achieved by this MOP improvement to information processing and sharing was found to be 39% for a 7-min initial mean delay and 52% for the 3-min updates (information generation time and delivery to the shooter).

8.5 *Architecture Four*

Architecture Four (hardware and software in addition to that required by the FOTC/GCCS/ACIXS integrated concept) represents change to information processing alone, without changing the information sharing procedure of the FOTC, but using separate assets. The information processing and sharing of this architecture uses supplementary hardware, functions and staff. From the available information on this architecture and as discussed previously, we assumed an initial total mean delay of 7 min and found a mean delay for updates of 3 min for the sensor-to-shooter information processing and flow. The maximum relative impact on OTH-T mission effectiveness for the hostile surface tactical picture on OTH-T of this MOP improvement to information processing and sharing was found to be 41% for a 7-min initial mean delay and 54% for the 3-min updates (information generation time and delivery to the shooter).

9. Future Contributions for the Fifth Command and Control Research and Technology Symposium

A brief summary follows of one of the topics that will be addressed by the author and by René Proulx at the Fifth Command and Control Research and Technology Symposium: Progress in Exploring Model-based Measures. The italic text is excerpted from our last report [15]. To it we have added, in plain type-face, fragmented results that support the prediction made (a year before these results were available). First we show the non-linearity of the impact of data aging on mission effectiveness, as illustrated by Figure 8. Next we comment on the rate of change of the impact of data aging on OTH-T effectiveness, which may follow the envelope of a Rayleigh density function, as Figure 9 shows.

9.1 *Impact of Data Aging*[17]

Using the same strategy for assessing the impact of data aging on the ITO measure or OTH-T mission success rate, we find a relative loss of 66.5% over 25.7 min if we combine the results for all the nodes (TWCS, FOTC and two SAGs). For the SEM it is 60%. These are equivalent to a loss of information value of 12.9% per five min, if we assume that it decreases linearly from the initial time each report is generated. For the SEM it is 11.6% per five min for all the nodes. At the FOTC we observe a shorter mean delay of 19.5 min and conclude for ITO 62.9% and SEM 55% degradations that the impacts of information aging are 16% and 14% per 5 min, respectively. The difference between these results and the previously reported values is primarily due to the assumption of a 25-minute mean delay, rather than the 20-minute delay reported here.

We do not expect the ***rate*** *of the impact of data aging to be linear (Dimpact / Dage is not linear). It is likely to follow a Rayleigh density function, with the value of the delay resulting in the maximum data-aging impact rate depending on the parameters of a MBM. We intend to investigate this aspect with the same data and models but by sorting the results as a function of the report delay for two sets of MBM parameters. Goodness-of-fit tests can be used to assess the*

[17] Not defined elsewhere in this paper. Intended-target opportunity (ITO), surface-action group (SAG), specific-engagement measure (SEM), pertinence-of-engagement (POE), Tomahawk weapon control system (TWCS).

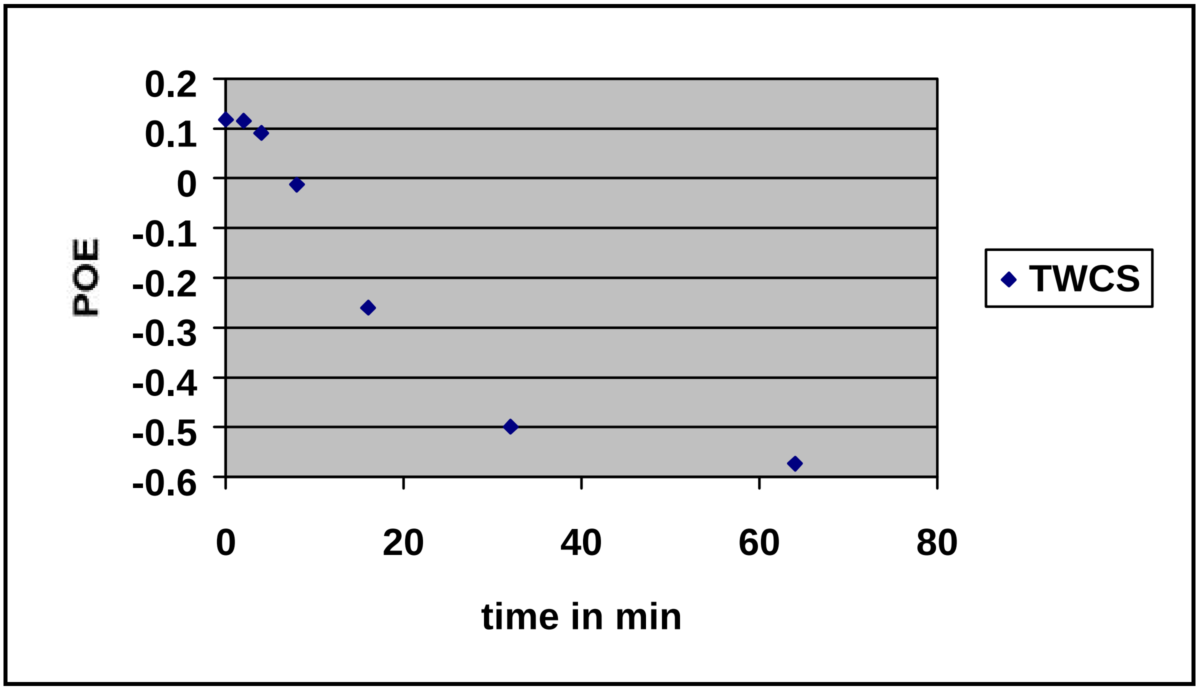

Figure 8. Intermediate results for illustrating the non-linearity of the impact of data aging

soundness of our hypotheses. We expect the maximum rate of data-aging-impact to occur at a delay close to 9 min for the current parameters. One may consider this value to be the critical information age for a decision, task or mission for a given success rate.

We have initiated some tests of these hypotheses. Figure 8 shows the non-linearity of the impact of data aging on mission effectiveness. Furthermore, Figure 9 clearly illustrates the non-linearity of the rate of the impact of data aging (i.e., Δimpact / Δage is not linear): the envelope has the shape of a Rayleigh density function. Though our sample is small it seems that the "critical time"—the time at which the rate of the impact of data aging reaches a maximum—is not exactly 9 min but some value larger than 8 min and smaller than 16 min. A higher sampling frequency or smaller time interval between our MBM results is needed to estimate this new information-system parameter, the "critical time," more accurately. This parameter may prove to be useful in characterizing the value of information in OTH-T in a manner less dependent on the various parameters of the MBMs. This is certainly an interesting avenue to explore.

9.2 Causality

Although links between MOPs and MOEs are implied by the ITO and POE MBM definitions given in Chapter 2, little has been said about the specific MOPs that are sensed by the six MBM models used. A tentative identification follows of the sensitivity of MBM models to certain MOPs: their ability to link a particular MOP to the OTH-T effectiveness of a warship.

9.2.1 Relevant MOPs

International organizations are attempting to define standard sets of MOPs to assess command and control information systems and to allow fair comparisons of test results, but there is still no recognized standard definition and "code-of-practice." The MOPs summarized in Table 1 are, in the opinion of one of the authors, those needed to demonstrate the value of MBMs.

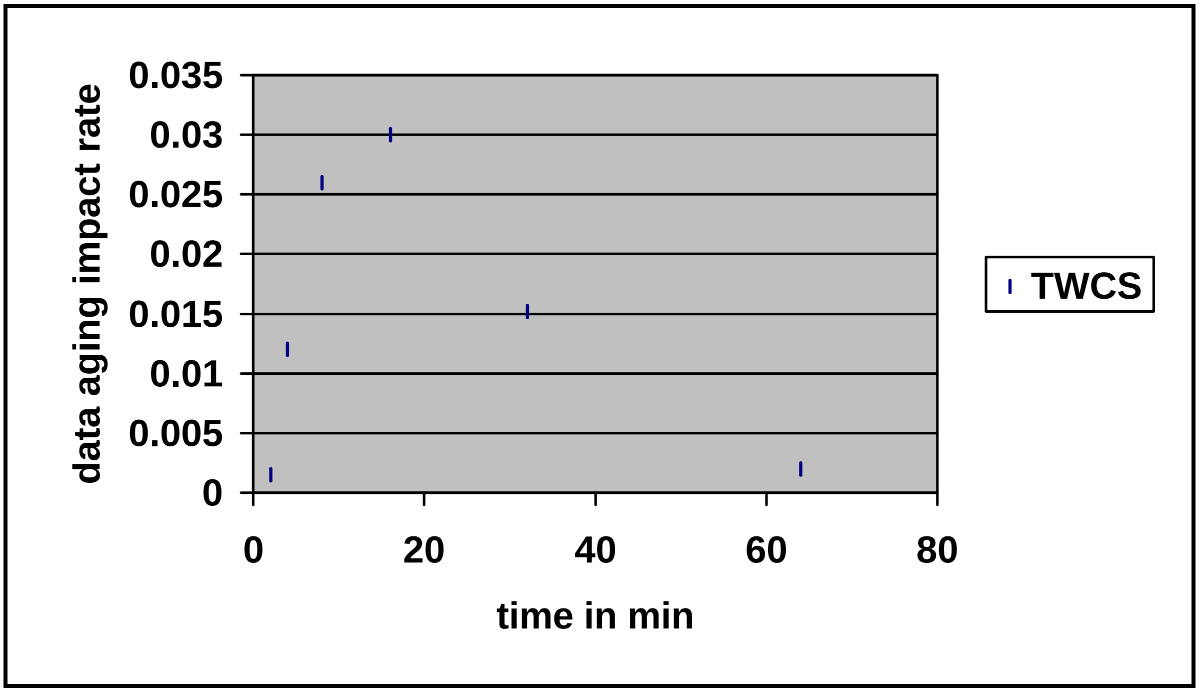

Figure 9. Rate of the impact of data aging per unit of time for Day 3; a Rayleigh envelope?

9.2.2 Examples of Causality Dependence of MBMs

In Table 2 we show that a combination (relative or differential) of Models 1 and 2 at the FOTC is a good causal indicator of the impact of information currency, management delay and timeliness for OTH-T. The combination of Models 1 and 4 is an indicator of identification correctness. Model 4 at the FOTC, relative to Model 4 at a SAG, is a good causal indicator of information coherency, but with particular emphasis on the information exchange loss between the FOTC and the SAG, while the Model 5 combinations for these databases give indications of information coherency, currency and timeliness but with emphasis on information-exchange delay.

Such mapping of MBM dependence and indications of the impact of MOPs on the mission success rates needs further investigation and will be the subject of further research.

The author will address several issues related to MOP and MOE definitions and relations in terms of MBMs in another report. A related document has been published recently by NATO: *NATO Code of Best Practice for C2 Assessment (draft)*. It is available on the C4ISR[18] Cooperative Research Program (CCRP) server: “http://www.dodccrp.org/default.htm”. It will be interesting to extend MOP (Table 1) and MOE definitions and relations for future MBMs to harmonize our results with those that will follow the recommendations of this international standardization effort. Common goals, scenarios, operational and environmental conditions, architectures, testing procedures and measure definitions should then deliver results that are similar, if not necessarily identical.

Much research remains to be done and standardization efforts in this area should encourage creativity, not stifle it.

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[18] Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR)

TABLE 1
Selected measures of performance

MOP	*description*
allegiance correctness	*The probability that the allegiance assigned to the contact is correct. This is a condition for identification correctness.*
identification correctness	*The probability that the unique identification of the contact is correct.*
information coherency	*Information or picture coherency among participating units indicates the percentage of data shared simultaneously within a given time window and geographical area, for a particular type of data required for a task.*
information completeness	*Information or picture completeness at each database is the percentage of data that is correct and timely, relative to the available data from all sources (ideally the ground truth). It may be defined for a particular task.*
information conciseness	*Information or picture conciseness is the quantity of data in a database that is "free from all elaboration and superfluous detail" divided by the total number of data items. The maximum value is one.*
information currency	*Information currency is inversely proportional to data aging. The age of the data is the elapsed time since last report before consideration (sampling time). It may include time delays from any of the processing stages. Once related to a required decision or task time for a given success rate it becomes the timeliness of that information for an opportunity.*
information exchange delay	*The time required for exchanging information from one database to another. It impacts the inter-database coherency and currency.*
information exchange loss	*The amount of information loss from one database to another. It impacts the inter-database coherency.*
information management delay	*The time required to process a contact report from the time it is generated by the source or sensor to the time it enters the local database and becomes accessible for decision making.*
position accuracy	*The relative or geographical precision of the position of a contact (may include estimations of speed, altitude and attitude). It is usually expressed in terms of areas or values of uncertainty.*
timeliness	*Timeliness is how timely a piece of information is for a task or decision. To be distinguished from information currency.*

TABLE 2
Mapping of MOPs on the MBMs assuming three levels of dependence: "d" for strong dependence, "i" for strong independence and "w" for weak dependence ("a" for the FOTC and "b" for a SAG).

causality	***MBM model number or combination of numbers***									
	POE			***ITO***			***combination***			
MOP	*1*	*2a*	*2b*	*4*	*5a*	*5b*	*1a:2a*	*1:4*	*4a:4b*	*5a:5b*
allegiance correctness	*d*	*d*	*d*	*d*	*d*	*d*	*i*	*i*	*i*	*i*
identification correctness	*i*	*i*	*i*	*d*	*d*	*d*	*i*	*d*	*i*	*i*
information coherency	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*d*	*d*
information completeness	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*w*	*w*
information conciseness	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*
information currency	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*i*	*i*	*d*
information exchange delay	*i*	*i*	*d*	*i*	*i*	*d*	*i*	*i*	*i*	*d*
information exchange loss	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*d*	*w*
information management delay	*i*	*d*	*d*	*i*	*d*	*d*	*d*	*i*	*i*	*i*
position accuracy	*d*	*d*	*d*	*d*	*d*	*d*	*w*	*i*	*i*	*w*
timeliness	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*i*	*i*	*d*

Table 2 is a tentative mapping of MOPs on MBMs and some of their combinations.

10. Conclusions and Recommendations

Change and continuity in the future of command and control, the highlight of this conference, is also the focus of this paper. Experimental data collected during coalition exercises have allowed new performance measures to be developed. *Change* is represented by the architecture changes whose impact on mission success rates we have assessed; *continuity* by the fact that we have accomplished this new assessment using the same information available to previous measures.

The data collected and the analyses presented support the following conclusions for the hostile surface tactical naval picture used for OTH-T (the improvement percentages are the maximum gains achievable for the MBM assumptions made, based on the hostile surface tracks in our data):

1. Of the 63% of potential improvement in the observed experiments, more than half is related to the transformation of sensor data into information and knowledge;
2. the remainder seems to be associated with FOTC broadcast procedures;
3. changes to improve FOTC broadcast procedures alone impact OTH-T by 22%;
4. changes to improve knowledge generation with 3-min updates alone impact OTH-T by 28%;
5. changes to improve both in a unified concept (GCCS/FOTC/ACIXS) impact OTH-T by 52%; and
6. changes to improve both but with the addition of staff and hardware impact OTH-T by 54%.

Due to the complexity and intricacies of C3IS and the fact that its impact on mission effectiveness cannot be measured as directly as can that of most weapon systems, further studies are required to explore the avenues touched on in this document. Nevertheless, the data used showed that the potential gain in OTH-T is relatively independent of specific systems changes but depends strongly on the ability of a particular change to deliver more timely, precise and appropriate information to the shooter. Changes that involve independent dedicated assets and systems, planned for one of the Joint Warrior Interoperability Demonstrations (JWID) in 1999, display the highest mission effectiveness gain. However, proliferation of distinct hardware and un-integrated concepts is not cost-effective in the long run. An alternative is to rely on the integration of the concept within the framework of Allied Command Information Exchange System (ACIXS), the Force Over-the-horizon Track Coordinator (FOTC) and the Global Command and Control System (GCCS), using a modified standard operating procedure (SOP) and appropriate middleware. We have shown that both possible implementation strategies could offer information with similar quality to the end user and consequently would improve mission effectiveness by essentially the same amount[19].

Since the effect of data aging is not linear, the reported percentages for the improved architectures will be slightly different but there seems to be sufficient evidence to stimulate further investigation of the problems and to explore GCCS/FOTC/ACIXS changes. More tight cooperation between the information sources, the communication networks, the systems used by the staff and the software agents representing the information requirements of the end users may prove to be particularly cost-effective in the long run. Since the assumption of infinite communications bandwidth, computing power and staff capacity has already proven to be disastrous in all real-world military operations, a search for efficient or smart ways to exploit these critical resources must be made a high priority.

Results presented in this paper support the Canadian Navy plan for cooperative engagement capability for national and coalition operations. These results indicate that for some of the missions requiring such capabilities, the Canadian architecture evolutionary plan for improved information

[19] The small difference in effectiveness gain is not significant considering the level of abstraction used in the evaluation of the value of each architecture change. More experimentation is required with precise descriptions and samplings of the information processing and sharing at play.

management and direct sensor-to-weapon information flow would improve mission effectiveness by factors in excess of 20% and up to 50%. The effective improvement depends on scenarios and on the changes implemented. More modeling and analysis are required to increase our confidence in the assessments of the impact of these changes on OTH-T.

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