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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
OCT 2009		**00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Value of Information in C4ISR Systems	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defence R&D Canada,Center for Operational Research & Analysis,101 Colonel By Drive, 6CBS,Ottawa, Ontario, K1A 0K2 ,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Maritime Domain Awareness and Counter Piracy, 26-29 October 2009, Ottawa, Canada

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**61**	

Value of Information in C4ISR Systems

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Canada

HISTORY

- USS Vincennes Incident

  On July 3, 1988, Iran Air Flight 655, a civilian airliner, was mistakenly identified as an attacking F-14 Tomcat fighter. It was shot down by the US Navy's guided missile cruiser USS Vincennes, killing all 290 passengers.

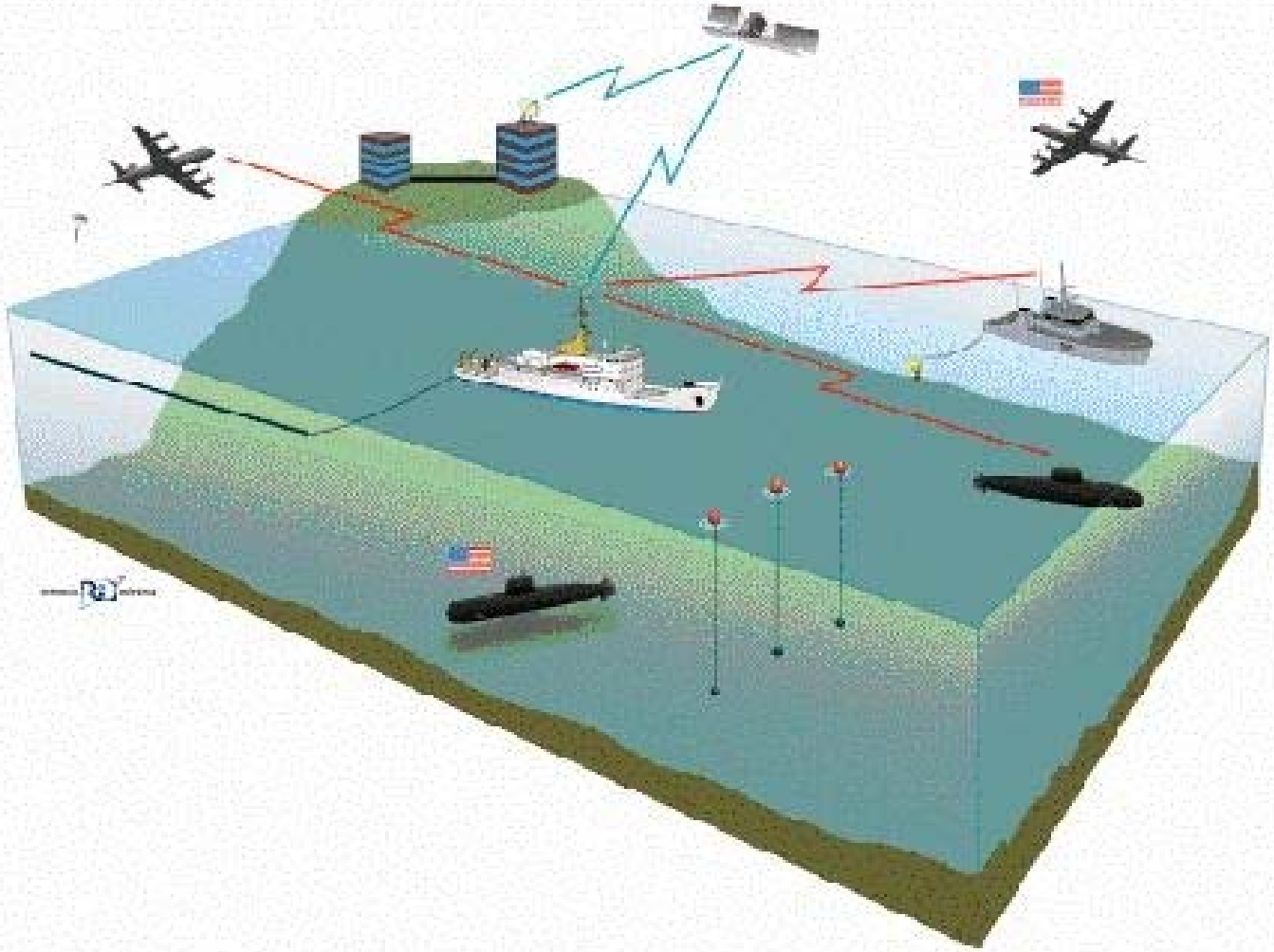
- Bombing of Canadian troops in Afghanistan

  On April 18, 2002, A US F-16 fighter jet mistakenly dropped at least one laser-guided bomb on Canadian soldiers that were taking part in a live-fire training exercise near Kandahar, Afghanistan.

VALUE OF INFORMATION ?

Timeliness

Quality



Introduction

- No military force globally has yet adopted a policy which permits fully autonomous detection, acquisition, tracking and weapon delivery against a target by a machine.
- Human beings still control the final decision on whether or not to fire a weapon against a target.
- Unless a high confidence level can be achieved in identifying a target as conclusively hostile, there is a genuine risk that human interpretation of sensors, and limitations in sensors will result in friendly fire.

Sensor operators onboard platforms used in the AWACS/AEW&C/ISR roles are the frontline troops in network centric operations: filtering, analysing and redirecting information when and where it is needed. (USAF)

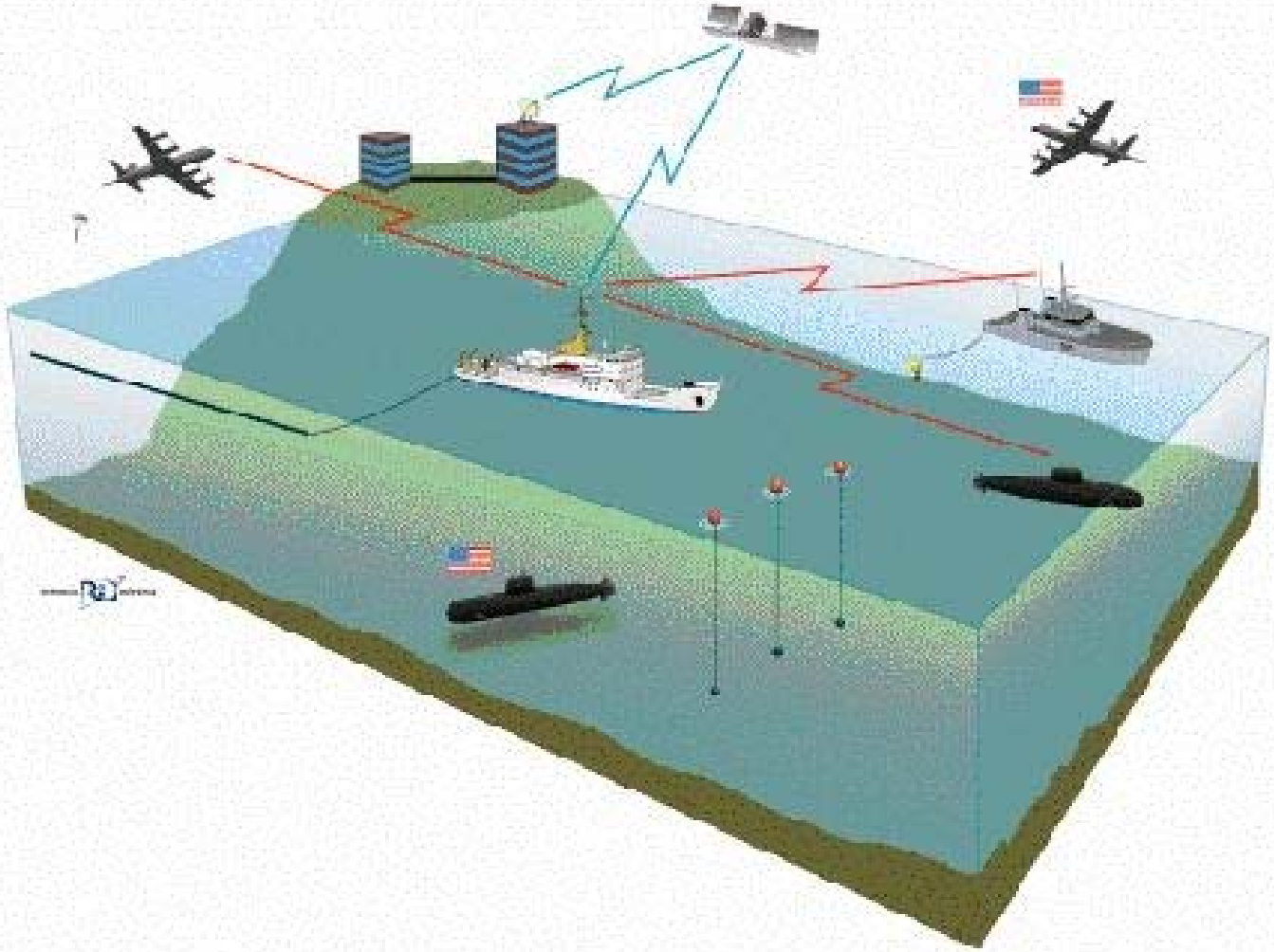
- In C4ISR or network centric system, humans are often required to extract, interpret and validate information from raw data at one or more points along the path from source to users. Humans are slow and prone to error.
- What is the *'value of information'* for C4ISR systems under the influence of human error?

Quantifying ‘Value of Information’

***U*(*timeliness*, *quality*) =**

f(*U*(*timeliness*), *U*(*quality*))

Multi-attribute Utility theory decomposes the joint Utility function into a function of individual single-attribute utility function.



DRDC Networked Underwater Warfare Experiment

- To demonstrate the effectiveness of a network of sensors and platforms to detect, classify and localize underwater targets.
- The experiment employed an IP network over UHF radio links to connect different platforms – maritime patrol aircraft, surface ships, submarine (source) to the command and control headquarter (sink).

Communication Net in “Networked Underwater Warfare”

- What kind of digital (radio frequency) datalink and network configuration would be required to minimize system response time (timeliness)?

‘Timeliness of Information’

- Timeliness

  ≡ ‘sensor-to-shooter’ interval

  = time delays in transmission and datalink relays

  +

  time delays experienced in filtering, analyzing and redirecting information by human operators

Constraints

Issues on datalinks and network:

- Security of transmission
- Robustness of transmission
- Transmission of capacity or throughput
- Communications protocol compatibility

Additionally, communication link capacity is strongly constrained by

- power aperture,
- footprint,
- physics of radio propagation
- sensor bandwidth mismatch

Timeliness Formulation

Timeliness of information in network

= Transmission, queueing, propagation delay in communication network

+

Time required by human (operator) minds to process information

+

Time required for quality evaluation of human operator activities in interpreting information

Transmission, queueing, propagation delay in communication network (stationary nodes) - exact solution

- ***Minimize*** *average source–destination packet delay*

  (*M/M/1* queueing network)

subject to

nonlinear cost constraint to reflect scale of economy in bandwidth (capacity) cost

flow demand satisfy the *multi-commodity flow*

threshold reliability constraint
(Probability of successfully transmitting a specified flow requirement from source to terminal node; function of link connection, link capacity and flow demand)

capacity and flow variables - *integers*

- L. Kleinrock
  Communication Nets: stochastic message flow and delay, *Lincoln Lab Publication*, *MIT thesis* 1964.

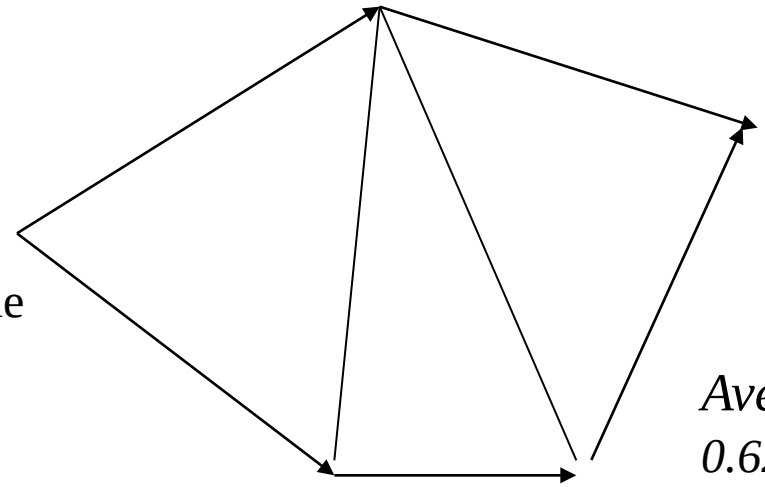
D. Bertsekas, Data Network, 1992

C. Jane and Laih
Algorithms to determine the threshold reliability of flow networks, *IIE Trans*., 2004

K. Ng & Sancho
A hybrid dynamic programming/depth first search algorithm, *IIE Trans*., 2002

K. Ng
Improved feasible solutions for redundancy allocation in complex systems, conditional acceptance, *IEEE Trans*. 2009

- Total requirement, packets/sec
- Given upper bound on bandwidth, kbps
- Threshold reliability upper bound
- Packet size represented by exponential distribution with given mean, bits/packet



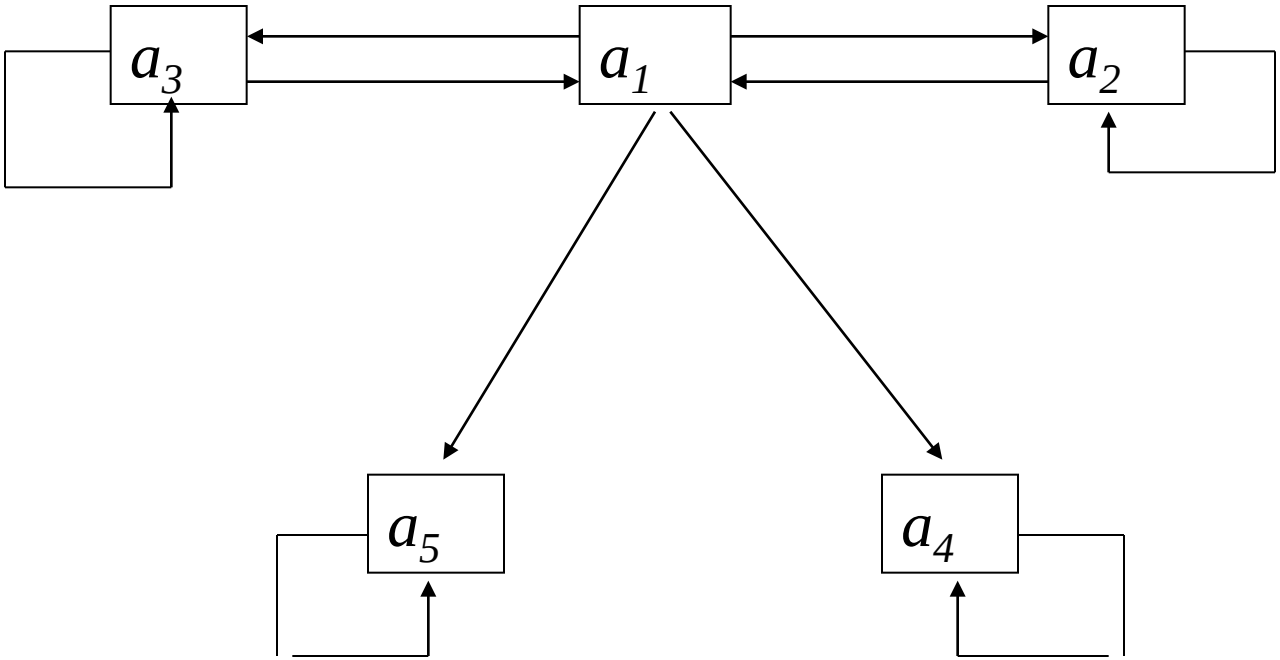
Average delay
0.6274 10^{-1} *sec/packet*

Sensor operators onboard platforms used in the AWACS/AEW&C/ISR roles are the frontline troops in network centric operations: filtering, analysing and redirecting information when and where it is needed. (USAF)

Timeliness Assessment
Quality evaluation of human activities – Markov Chain formulation

- *a1* = entering supplementary information;
- *a2* = withdrawing supplementary information when information was *correctly entered* and operator made a *wrong decision*;
- *a3* = withdrawing supplementary information when information was *incorrectly entered* and operator made a *good decision*;
- *a4* = end situation; when supplementary information was *correctly entered* and operator made a *good decision*;
- *a5* = end situation; when supplementary information was *incorrectly entered* and operator made a *wrong decision*.

Graph of the process of entering supplementary information



a_1, a_2, a_3 transient states, a_4, a_5 absorbing states

p = probability that operator enters supplementary information incorrectly;

p_d = probability that operator's decision is wrong;

p_c = probability that operator withdraws information incorrectly;

Elements of Transition matrix

0	$(1-p)p_d$	$p(1-p_d)$	$(1-p)(1-p_d)$	pp_d
$1-p_c$	p_c	0	0	0
$1-p_c$	0	p_c	0	0
0	0	0	1	0
0	0	0	0	1

- Canonical Form

$$\begin{matrix} Q & R \\ 0 & I \end{matrix}$$

where Q is transient matrix, I is identity matrix, R is absorbing matrix

Using Absorbing Markov Chain Theory, the expected number of steps before the chain is absorbed can be calculated via the fundamental matrix given by

$$(I - Q)^{-1}$$

Example

- Probability that human operator enters the supplementary information incorrectly = *0.15*
- Probability that human operator withdraws information incorrectly = *0.15*
- Probability that human operator's decision is wrong = *0.5*
- Assume average time required between transition of states = *5 secs*.
- *Delay time* caused by the quality evaluation of human operator activities in interpreting information = *8.236 secs.*

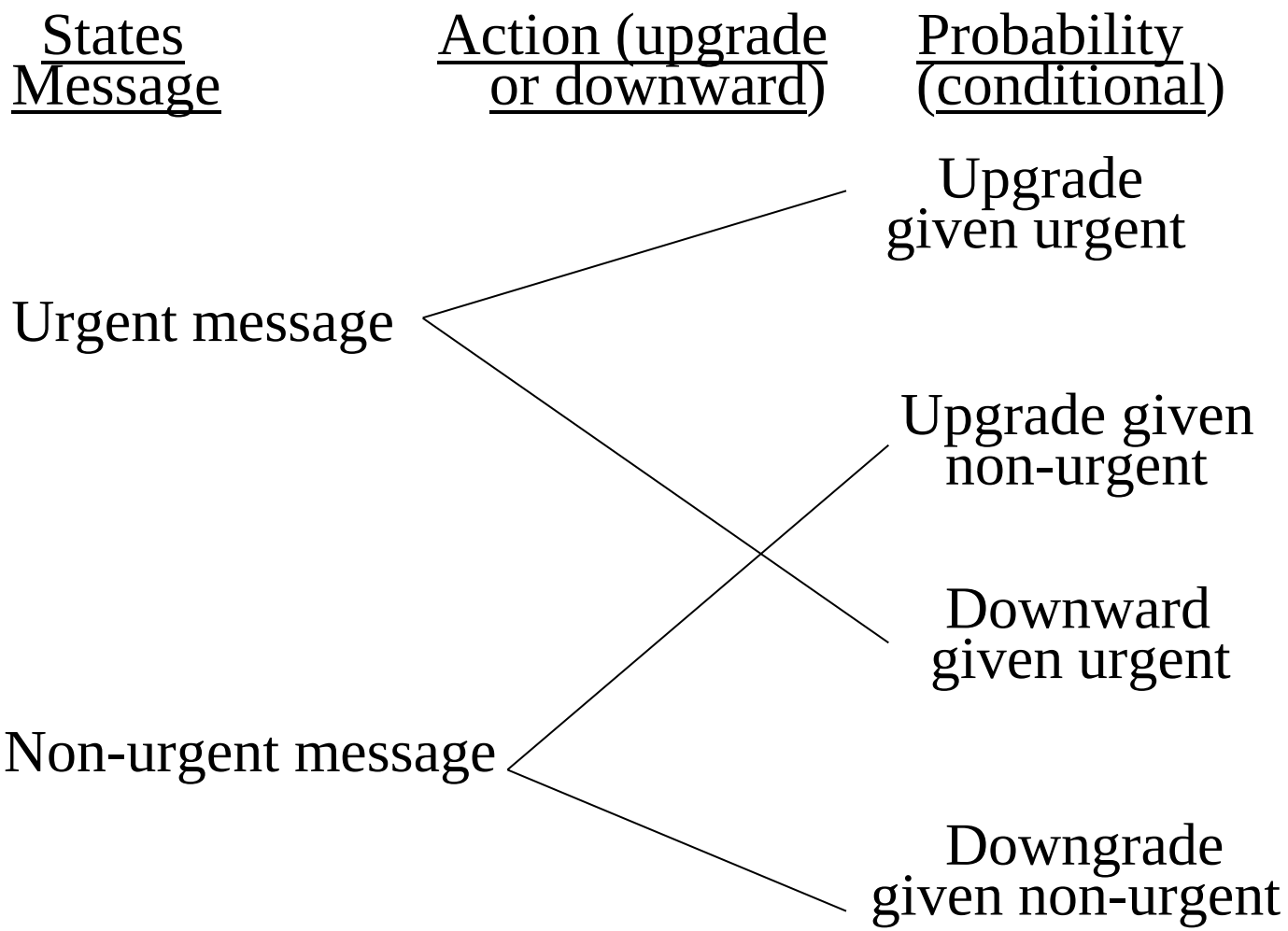
Theoretical framework – Quantifying Timeliness

Timeliness of information in network

= Transmission, queueing, propagation delay in communication network
+ Time required by human (operator) minds to process information
+ Time required for quality evaluation of human operator activities in interpreting information

Computer-communication network analysis
+
Absorbing Markov Chain Theory

Quantifying 'Quality of Information'



Quantifying ‘Quality of Information’

- Incoming messages with 2 states

  - urgent (important)

  - non-urgent (standard, routine)

  Courses of action by human operators

  - priority upgrade (provide supplementary information)

  - priority downgrade (no supplementary information provided)

Quality of Information

- **Minimize chance to upgrade non-urgent messages**

- Minimize the conditional probability

  P(non-urgent message given priority upgrade)

$$P(\text{non-urgent} \mid \text{upgrade}) = \frac{P(\text{upgrade} \mid \text{non-urgent})\, P(\text{non-urgent})}{1 - P(\text{downward})}$$

Sensor operators onboard platforms used in the AWACS/AEW&C/ISR roles are the frontline troops in network centric operations: filtering, analysing and redirecting information when and where it is needed. (USAF)

Incoming message subject to Partial Examination

- Assume the total number of available human operators at the Command & Control Center be *M*.
- An incoming message will be examined randomly by *m* operators, $m \leq M$. The rest of the messages will automatically be upgraded and supplied with supplementary information.

Incoming message subject to examination randomly by '*m*' human operators,

$$P(\text{non-urgent} \mid \text{upgrade})$$

$$= \frac{P(\text{non-urgent})[\ 1 - m/M + m/M * P(\text{upgrade} \mid \text{non-urgent})}{1 - m/M * P(\text{downgrade})}$$

Quality of Information

- Despite errors made by human operators, increasing the frequency of incoming message validation by multiple operators will increase the likelihood of detecting errors and thus improving the quality of information

Quality of Information

Theorem

If $P(\text{downgrade} \mid \text{urgent}) < 0.5$,

$P(\text{upgrade} \mid \text{non-urgent}) < 0.5$,

then $P(\text{non-urgent} \mid \text{upgrade})$

decreases

as the frequency of incoming message validation by multiple operators,

increases.

Quantifying ‘Value of Information’

***U*(*timeliness*, *quality*) =**

f(*U*(*timeliness*), *U*(*quality*))

Multi-attribute Utility theory decomposes the joint Utility function into a function of individual single-attribute utility function.

Metric for C4ISR Systems

- Provide a baseline for comparing C4ISR systems.
- Redefine the rules of engagement in networked operations or combat.
- Provide a decision tool enabling military forces to recognize and exploit opportunities to integrate sensors, weapons, and platforms in optimal NEC/NEO architectures to achieve greater value from future capital investments.
- Improve force effectiveness, decrease combat casualties due to enemy actions and to decrease confusion-related friendly fires.

Simulation Approaches

- ABSNEC
  Agent based Simulation for Network Enabled Capabilities
- DRDC CORA designed agent-based simulation system

Ref. K. Ng, M. Rempel,

ABSNEC – An Agent-System for Network Enabled Capabilities/Operations, *Proceedings of the International Simulation Multi-conference, 2009,* IEEE Catalog Number: CFP0974

Battlefield-Specific ABM Toolkits

- **MANA (Map Aware Non-uniform Automata)**

  ISSAC/EINSTein

  WISDOM II

  BactoWars

- **Mostly land-combat Agent-Based Models, none of them can handle optimized networked operations**

DESIGN PHILOSOPHY -ABSNEC

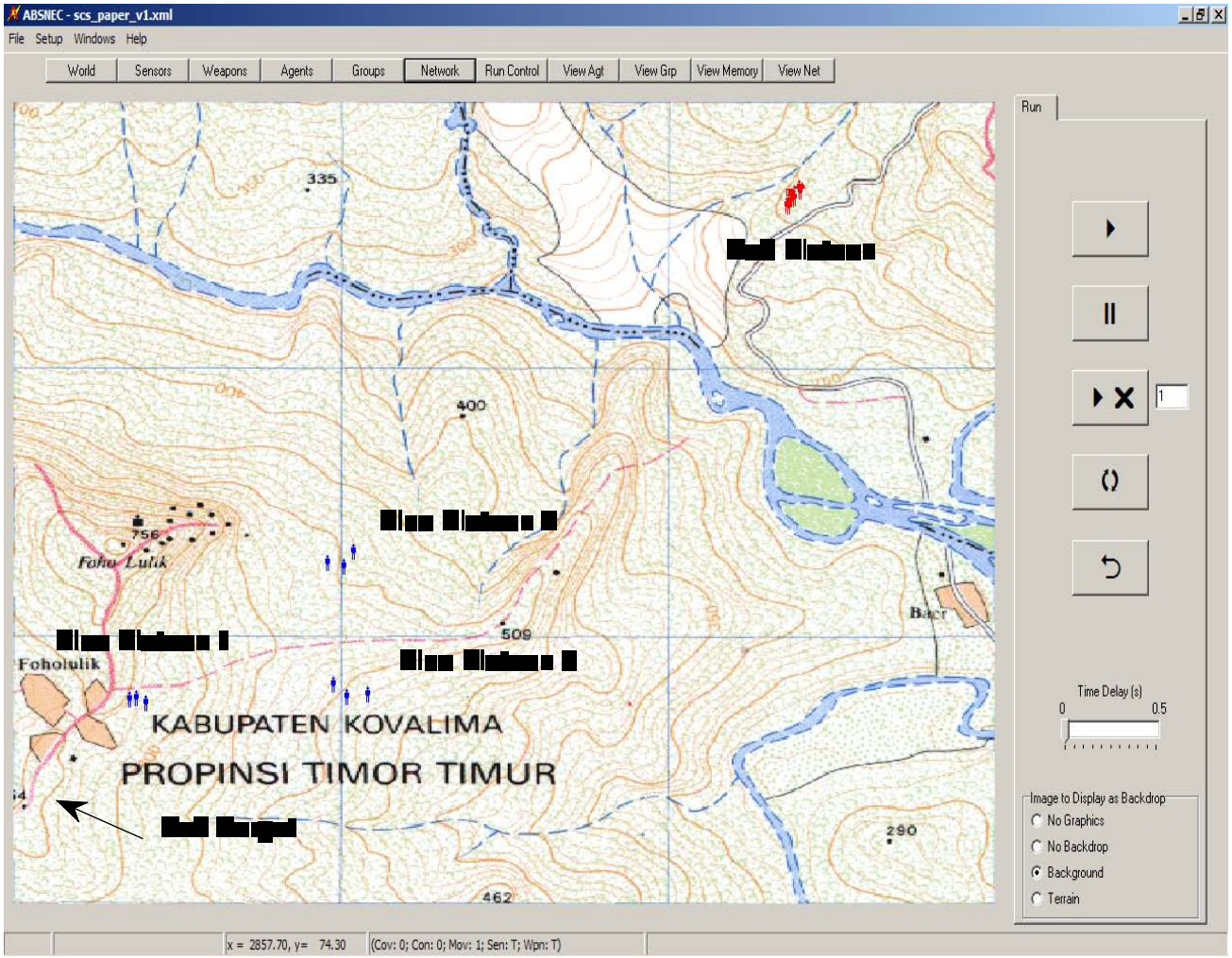
- **Framework/flexibility: majority of algorithms are fixed. Key areas, such as timeliness and quality of information, provide flexibility to user-specified algorithms.**
- **Platform complexity: complexity of user interface is minimized through a dynamic (object oriented design) Graphical User Interface GUI.**
- **Scientific tools/causality: scientific tools (e.g. statistical analysis) have not been included directly in ABSNEC. Third party software (e.g. MATLAB) used to perform analysis.**
- **Ease of installation and learning.**

ABSNEC DESIGN

- **a medium fidelity agent-based distillation model of military operations.**
- **possesses many features of current battlefield-specific ABMs – movement, weapons, physical capabilities, probability of detection etc.**
- **model the non-linear effects of C4ISR on operations through the creation of groups and commanders' orders.**
- **model intangible parameters – stress, cohesion, morale, fatigue, suppression, leadership, etc.**
- **integrate user defined 'timeliness and quality of information' analysis algorithms for networked operations.**

ABSNEC Development

- **Phase I – model current battlefield-specific ABMs, groups, commanders orders etc**
- **Phase II – enhanced networking capabilities through user-defined network capacity, flow assignment, reliability algorithms**
  - **– user-defined algorithms to model intangible parameters**
- **Phase III – user-defined quality of information algorithms**



Main graphical user interface GUI

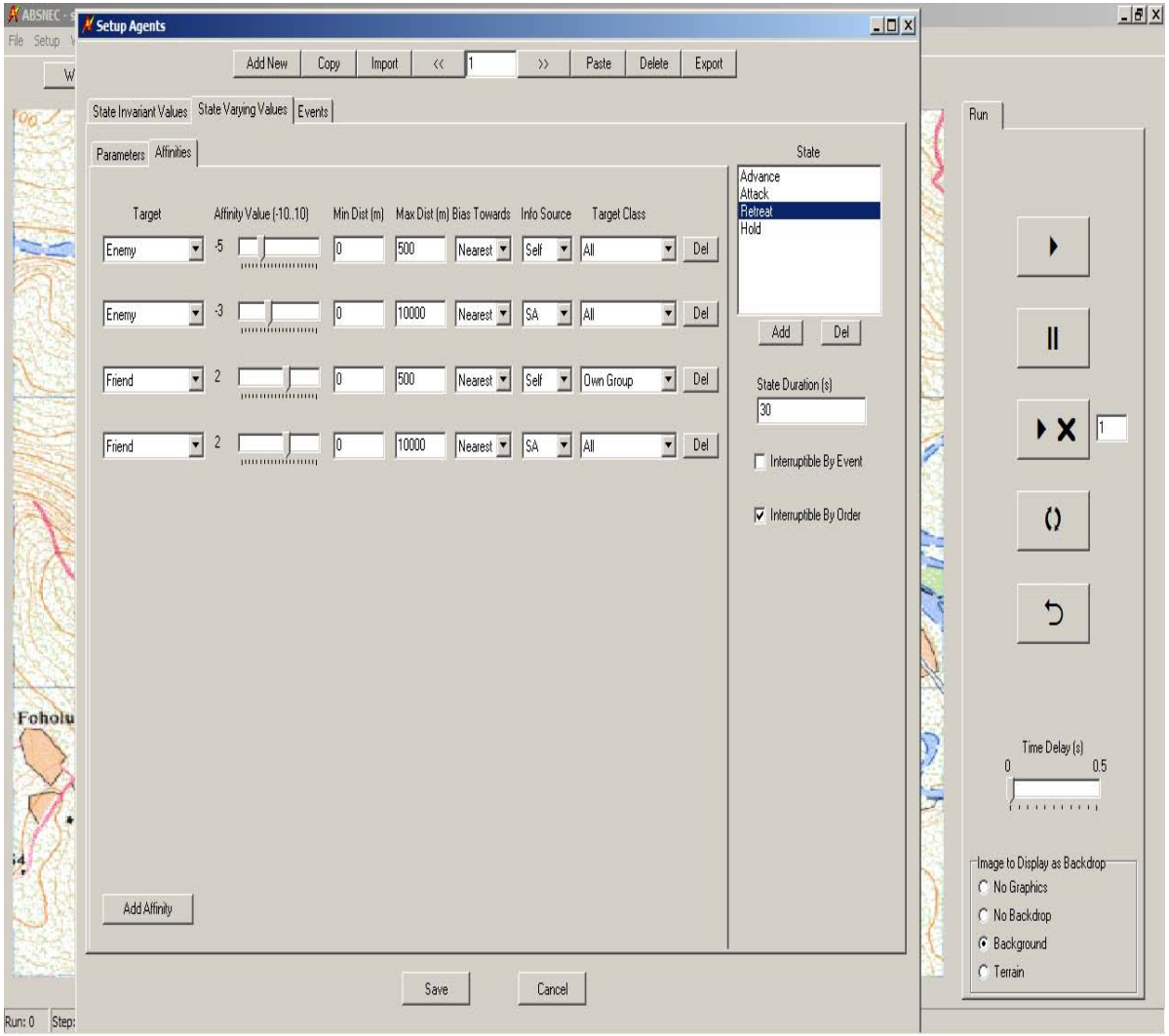
Distinctive feature of ABSNEC – object oriented design of key simulation objects

Agents

- may exist in a variety of user-defined states
- Each state includes

  a set of state-invariant (agent type, footprint size, etc) parameters

  a set of state-variant (speed, probability of detection, etc) parameters

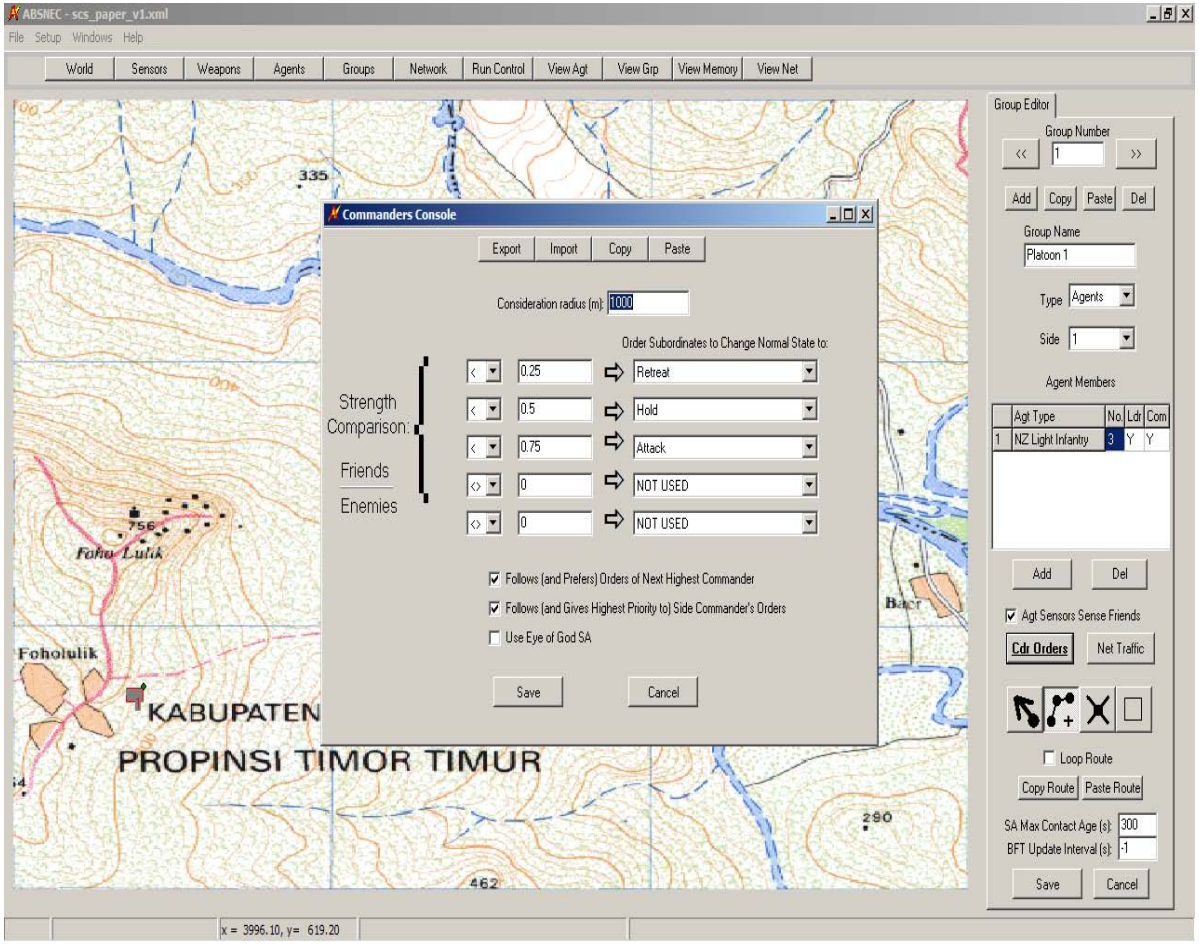


State-variant affinities GUI

Dynamic GUI allowing user to add/remove affinities

ABSNEC Phase I, Some Distinctive Features

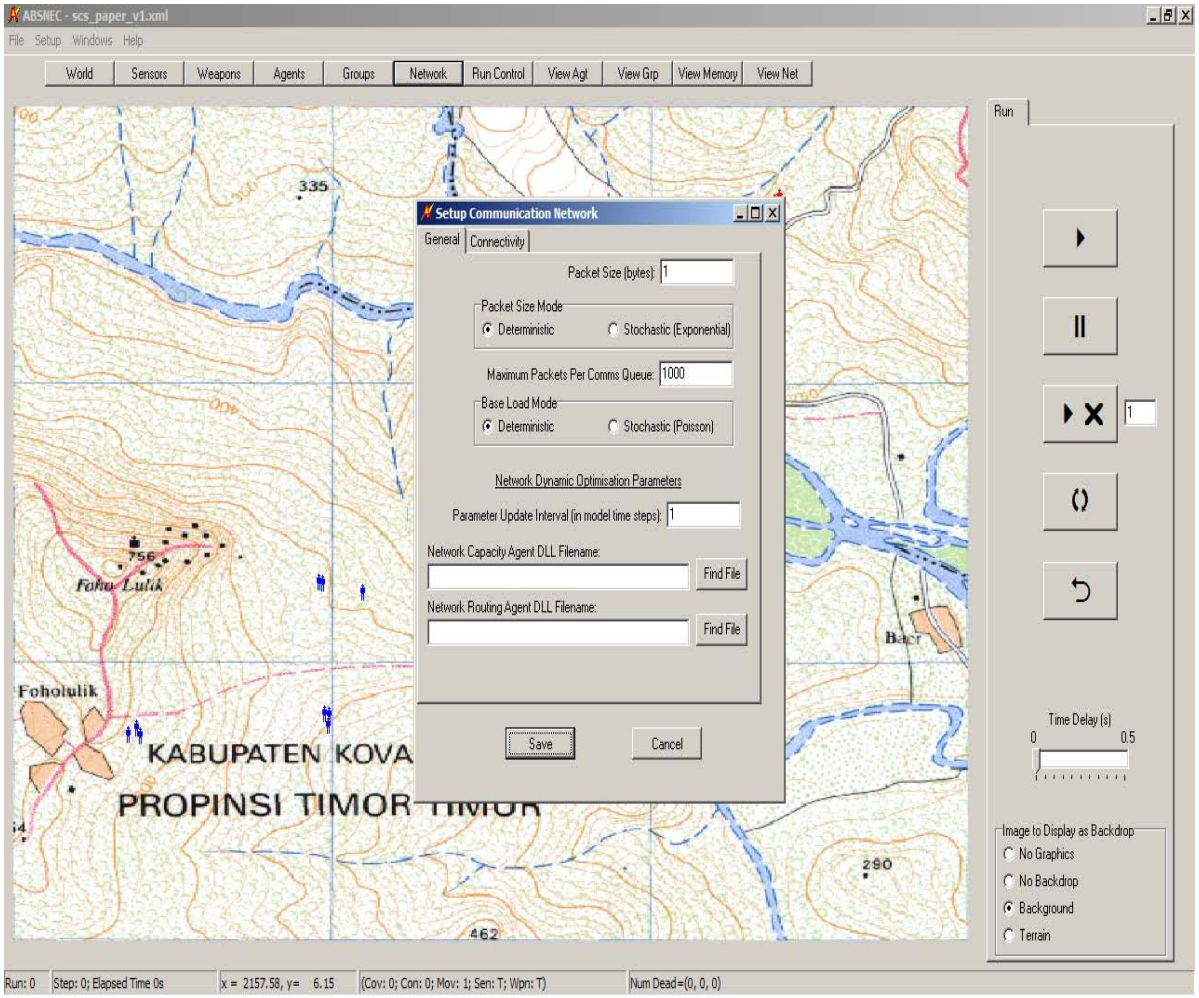
- **Hierarchical command structure - Groups and commanders' orders concept**
- **A group consists of either agents or existing groups. Within each group a commander agent, with a commander radius, may be identified which is responsible for issuing commands (order to switch state) to agents/groups within their group. Commands (user-specified) are based on a group's situation awareness map (SA).**



Commander's orders GUI

ABSNEC Phase II – Timeliness of Information for Networked Operations

- **User-defined algorithms for network capacity, flow optimization and network reliability**
- **Accomplished through the use of dynamic linked libraries (DLL)**



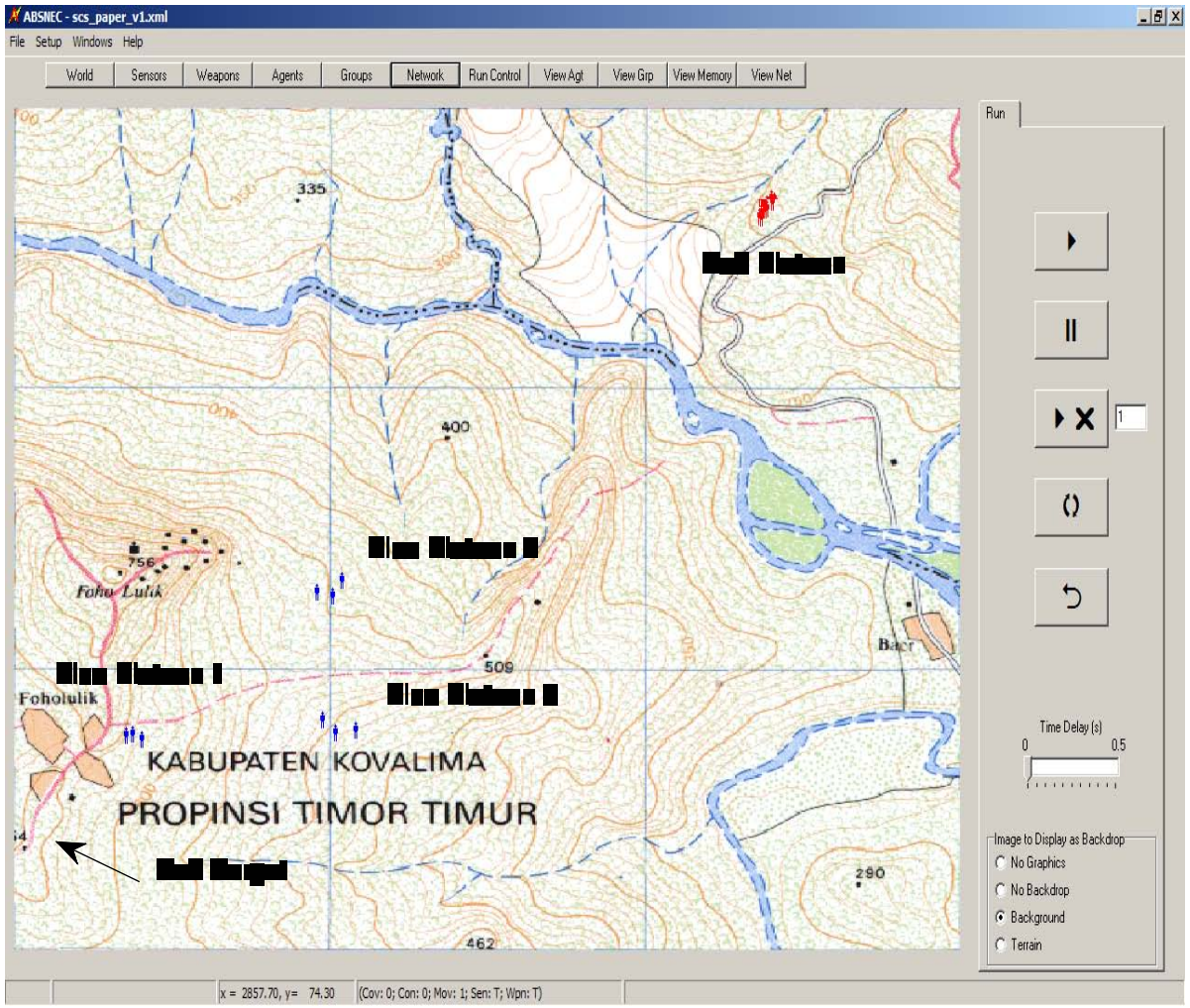
Graphical user interface to specify user-defined network capacity and flow algorithms

ABSNEC Phase III – Quality of information for Networked Operations

- **A similar design construct for ‘quality of information’ algorithms will be used.**

EXAMPLE on ABSNEC design – commander's orders and groups

- 2 opposing sides: a hostile Red platoon with 10 agents; 3 Blue platoons, each with 3 agents.
- Goal of Red platoon - transit from its initial position to its target destination
- Identical sensor, weapons with limited ammunition
- 2 scenarios: scenario A (baseline) with each Blue platoon acts independently; scenario B introduces a hierarchical command structure between a command headquarter and Blue platoons 2 and 3.


ABSNEC - scs_paper_v1.xml
File Setup Windows Help
World Sensors Weapons Agents Groups Network Run Control View Agt View Grp View Memory View Net
Run
335
400
509
462
290
756
Foho Lulik
Foholulik
KABUPATEN KOVALIMA
PROPINSI TIMOR TIMUR
Time Delay (s)
0
0.5
Image to Display as Backdrop
No Graphics
No Backdrop
Background
Terrain
x = 2857.70, y= 74.30
(Cov: 0; Con: 0; Mov: 1; Sen: T; Wpn: T)

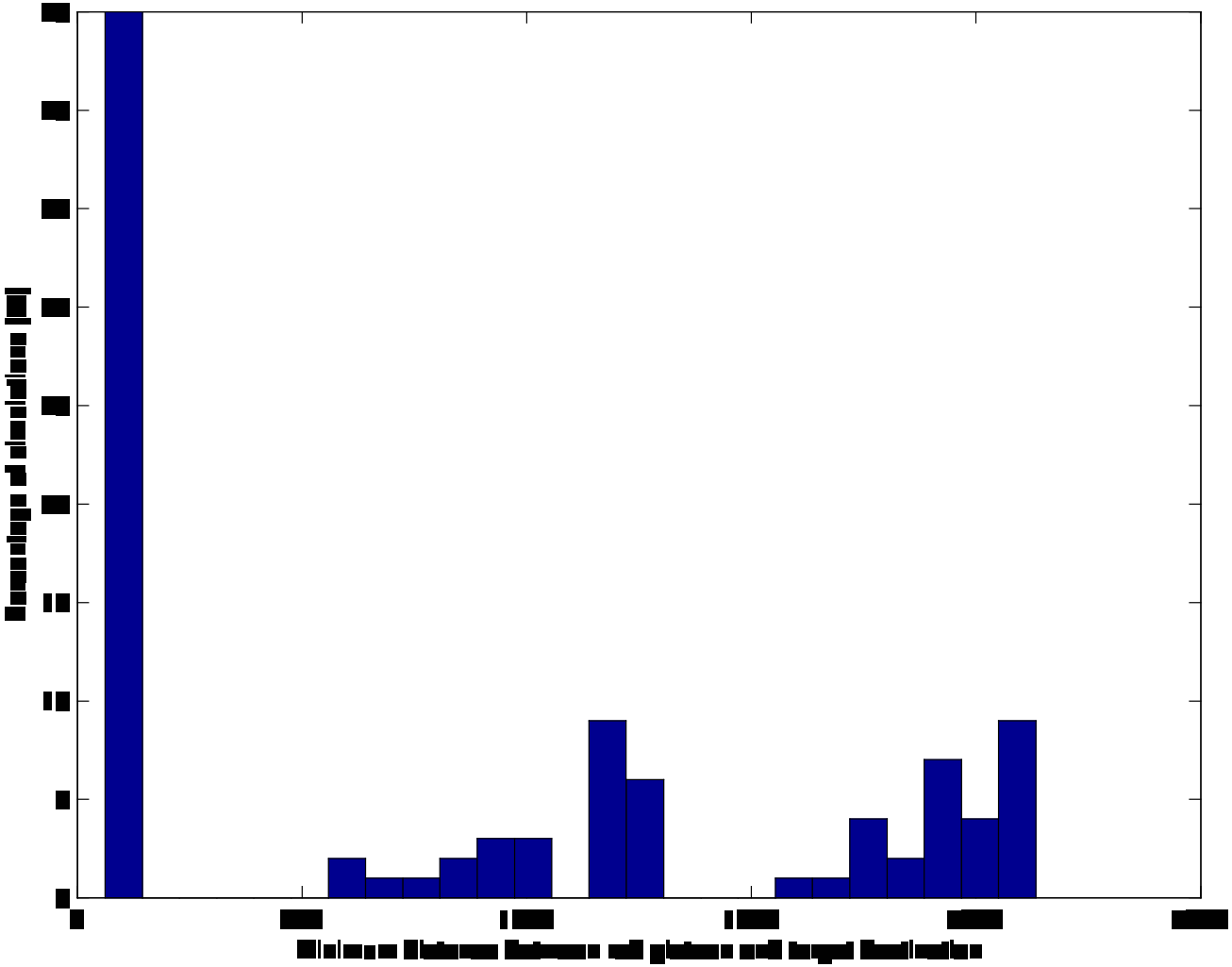
EXAMPLE cont'd

- **Blue agent states: Hold, Attack, Retreat with set of affinities**
- **Red agent states: Hold, Advance, Retreat with set of affinities**
- **Agent-state transitions are governed by their commander's orders**
- **Commander's orders are based on 'Friends-to-Enemies Ratio'**

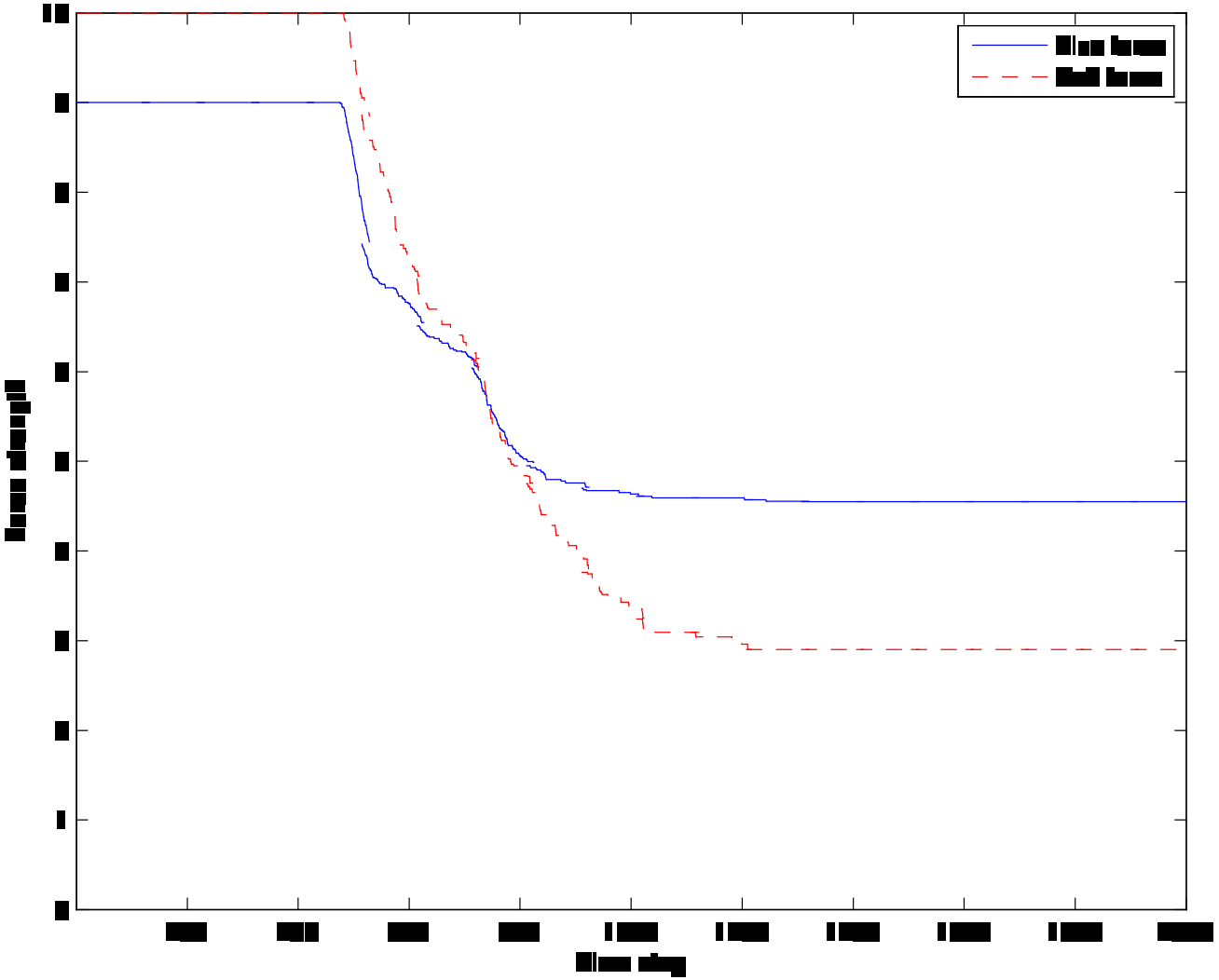
EXAMPLE cont'd

- **Scenario A (baseline scenario)**

  3 Blue platoons act independently with agent state determined by platoon's Situation Awareness map (SA)



There is a 45% probability that Red platoon reaches target destination

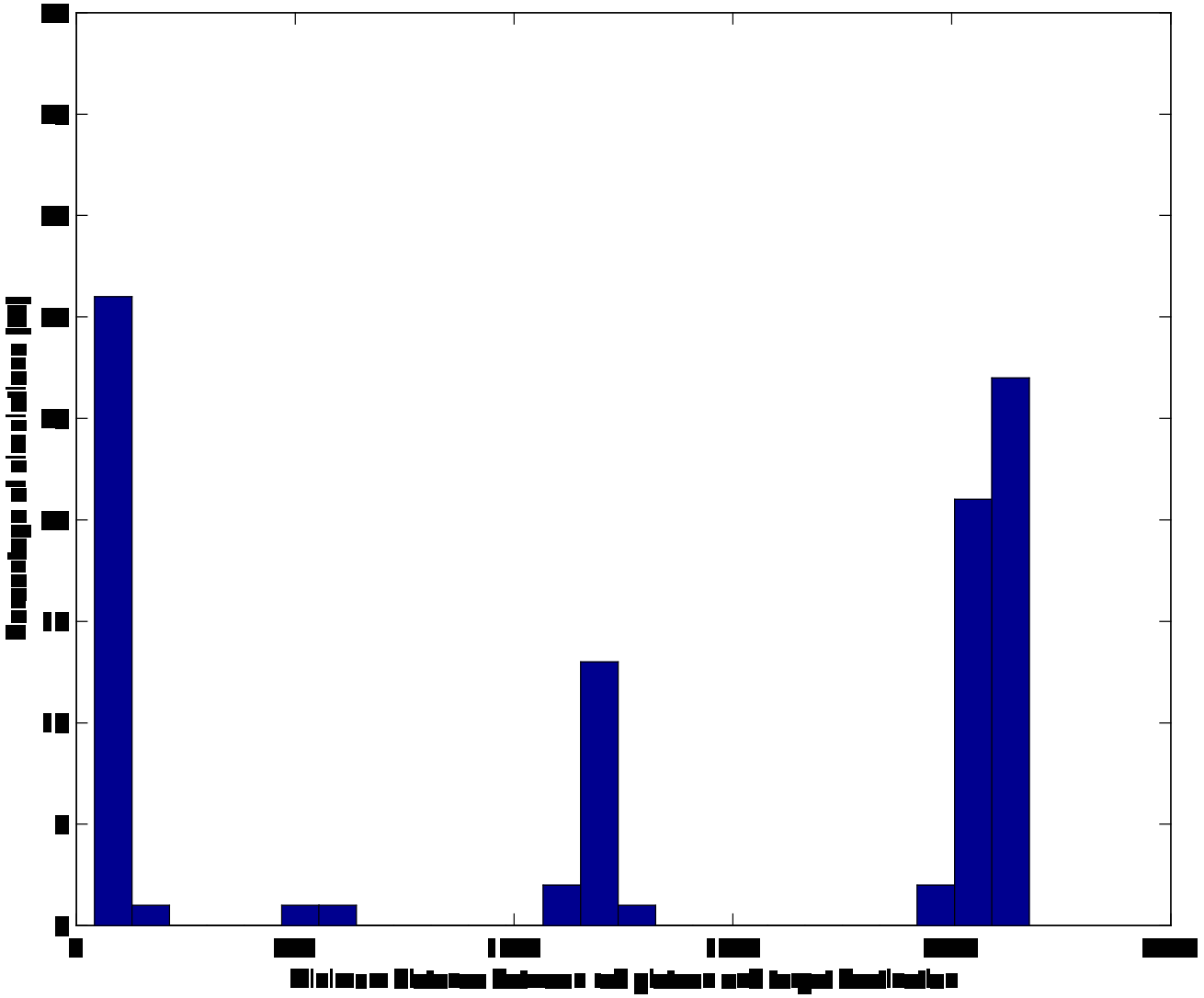


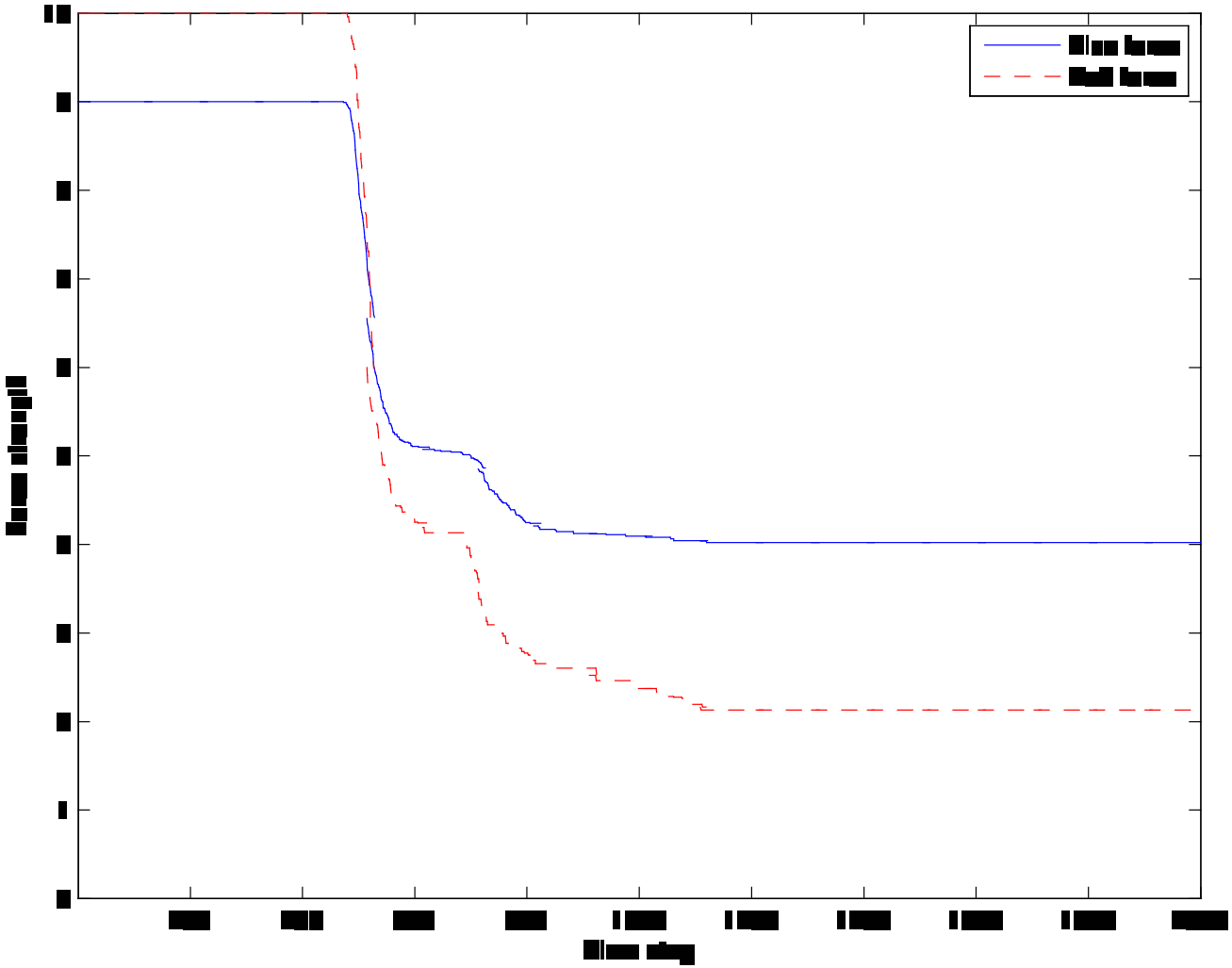
Blue and Red force strengths as a function of time,

average Blue force . . average Red force . .

EXAMPLE cont'd

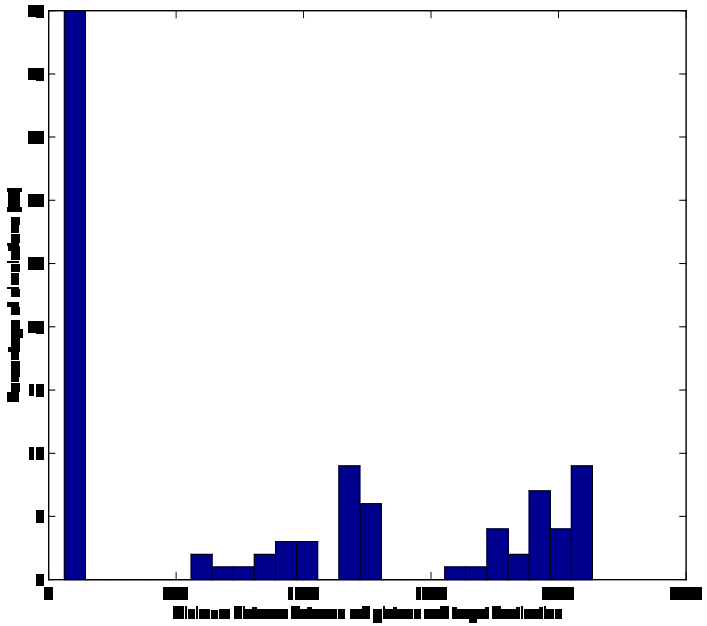
- **Scenario B – a hierarchical command structure,**
- **a network is setup between Blue 2, 3 and a command headquarter. The network is defined such that the 2 platoons send their SA to the headquarter and subsequently headquarter transmit the entire set of information to both platoons.**



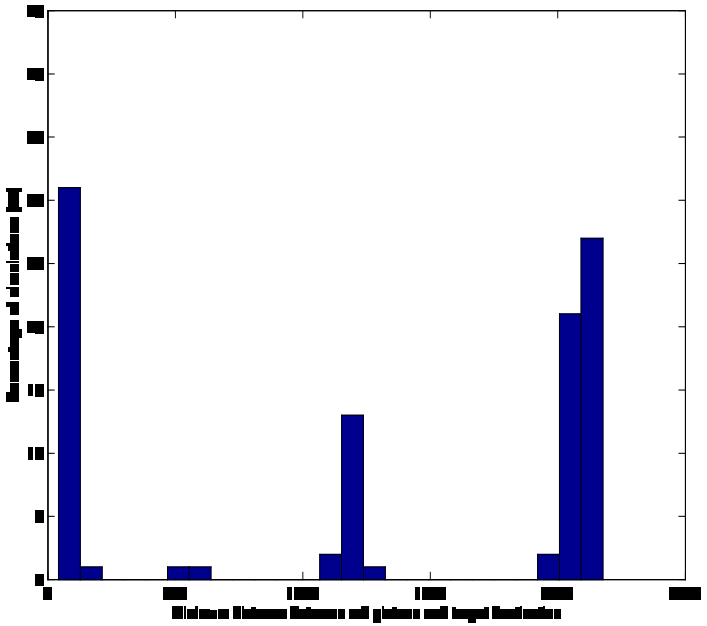


Blue and Red force strengths as functions of time

Comparison of minimum distance between Red platoon and destination target for Scenarios A & B



Scenario A – Blue acts independently



Scenario B – a hierarchical command structure for Blue

Comparison of force strengths between Red and Blue after 2000 time steps

	Blue	Red
Scenario A - no command Structure	4.5	2.9
Scenario B – Hierarchical command structure	4	2.1

OBSERVATION & CONCLUSION

- **At this early stage, Phase I of ABSNEC (i.e. land combat based features) parallels those of WISDOM II and is an improvement over the latest version of MANA.**
- **Phase II, III involve unique features allowing the analysis of ‘timeliness and quality of information’.**
- **Evidence from historical combat data suggests that action on battlefield obeys power-laws (common characteristics of complex systems). Propose using ABSNEC to explore impact of complexity on optimized networks - simulate military operation to study behaviour of communication traffic across an optimized network of finite capacity.**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