Informing Joint C2 System-of-Systems Engineering with Agent-Based Modeling: An Analysis and Case Study

LOCKHEED MARTIN

Chuck Lutz
Mitchell Kerman
Greg Schow
Mike DiMario
Ambrose Kam
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System of Systems (SoS) Definition

- **No accepted definition for SoS or SoSE**
- **Greater than 40 distinct definitions in authoritative open source publications [1]**
- **System of Systems (SoS) Definition (DoD):**
  - Arrangement of interdependent systems connected to provide a capability greater than sum of the member systems
  - Definition is augmented by characteristics

  [GAO "Defense Acquisitions DoD Management Approach and Processes Not-Well Suited to Support Development of Global Information Grid," January 2006.]
- **Family of Systems (FoS) Definition (DoD):**
  - Capability is summation of member systems
  - Grouping of systems with common characteristics
  - Does not acquire new properties or capabilities as a result of grouping

  [http://akss.dau.mil/dag/Guidebook/IG_c4.2.6.asp]

1. Boardman, J. and B. Sauser (2006). System of Systems - the meaning of *of*. 2006 IEEE International Conference on System of Systems Engineering, Los Angeles, CA.

Systems Engineering for
Large Scale System of Systems

- A Department of Defense perspective….

- Autonomous, semi-autonomous, and stand-alone systems
- Legacy systems
- Coalition systems
- Omnipresent protocols

Systems Engineering vs.
System of Systems Engineering

	Systems Engineering	SoSE
Scope	• Project/Product • Autonomous, well-bounded	• Enterprise/Capability • Interdependent
Objective	• Enable fulfillment of requirements • Structured project process	• Enable evolving capability • Guide integrated portfolio
Timeframe	• System Life Cycle • Discrete beginning and end	• Multiple, Interacting system life-cycles • Amorphous beginning • Important history & precursors
Organization	• Unified and authoritative	• Collaborative network
Development	• Design follows requirements	• Design is likely legacy-constrained
Verification	• System in network context • One time, final event	• Ensemble as a whole • Continuous, iterative

Source: Systems of Systems Center of Excellence

Network Centric SoS Example
Require Syntactic and Semantic Interoperability

Single Integrated Air Picture (SIAP)
- Common and Complete Pictures
- One Track per Air Object
- Continuous Track

Combat Identification (CID)
- Long Range
- Wide Area
- Improve Shooter Confidence

Integrated Fire Control (IFC)
- Employ independent of organic radar
- Overcome Radar Horizon Limitation

Automated Battle Management Aids (ABMA)
- Determine Optimum Weapons and Sensors
- Efficient Weapon and Sensor Management

Autonomous and Interdependent Systems To Form Holistic Capabilities

Traditional analysis

- Unbounded
- Solutions reflect modelers bias
- Could be worse than doing nothing since their impression is built that effort expended is productive

- **Need to expand the scientific and engineering basis for the development of software that is surprise free.**
- **Validation of theoretical research principles.**
- **Relate research to real world applications**
  - That will provide understanding about which architectural approaches work the best

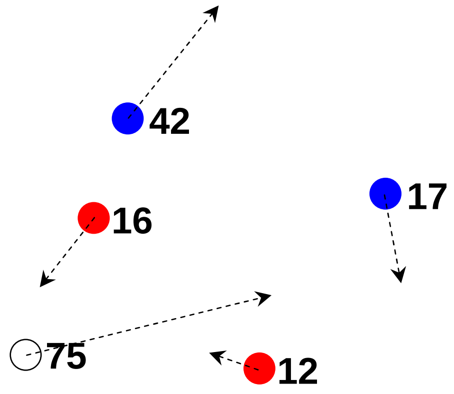
Conclusion

- These metrics may be a first in quantifying the effectiveness of systems engineering and software engineering.
- It will provide a baseline to measure future applied research projects
- Paper will be prepared to submit to Systems Engineering, the Journal of the International Council Of Systems Engineers (INCOSE)

CCID-CRA ABM Overview

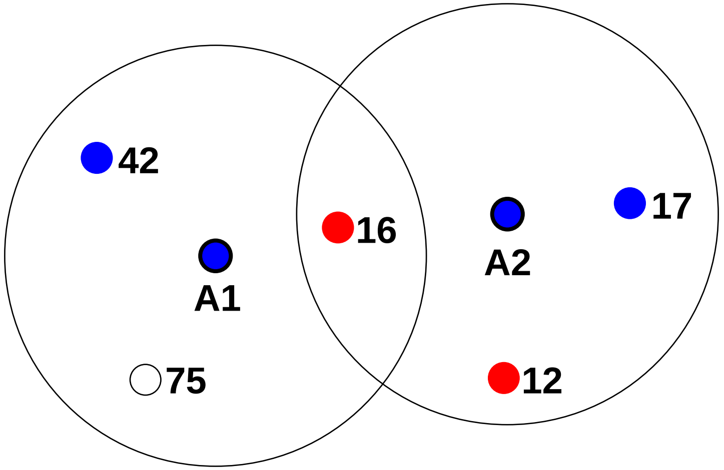
ABM CCID-CRA Model Basics: Simulation Setting / Ground Truth

- **Agents have attributes specifying their ground truth status**
  - – Allegiance: FRIEND, NEUTRAL, or FOE (Blue, White, or Red, respectively)
  - – Nationality: FRNAT1, FRNAT2, NUNAT3, NUNAT4, FONAT5 or FONAT6
  - – Type:
    - Air: JSF, E-2C, F6, etc.
    - Surface: CVN, DDG, LCS, FFG, etc.
    - Subsurface: Kilo, SSG, SSK, etc.
- **Agent populations specified on a per-agent basis**
  - – 11 Agent sets defined for two run matrices
- **Speed and Movement**
  - – Agents have a specified min and max speed range
  - – Agents, upon creation, have a random heading (static) and are assigned a random speed value within their range
  - – Agents move in a straight line at constant speed



ABM CCID-CRA Model Basics: Two Communicating Blue Nodes (I)

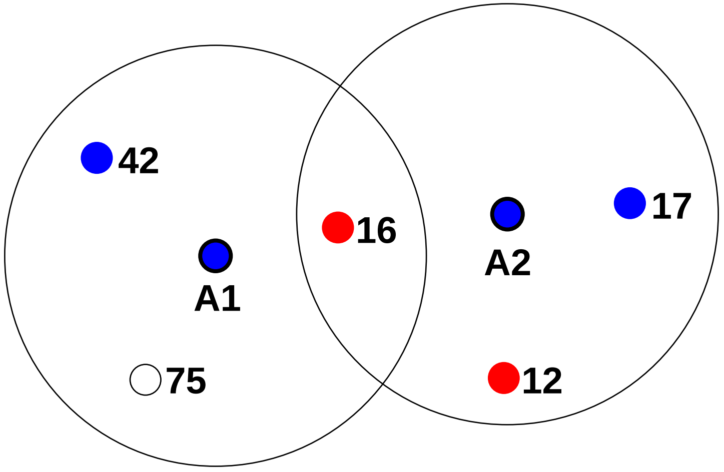
- Consider two blue agents, “A1” and “A2”, not within mutual sensor range, but have one sensed object in common
- A1 and A2 will detect objects in their range and produce tracks according to their sensor mix (previous example)
- Design Simplification: All agents share track numbers, and these are 100% reliable. Thus, we do not do any real track correlation (we have a simplistic “fusion”)



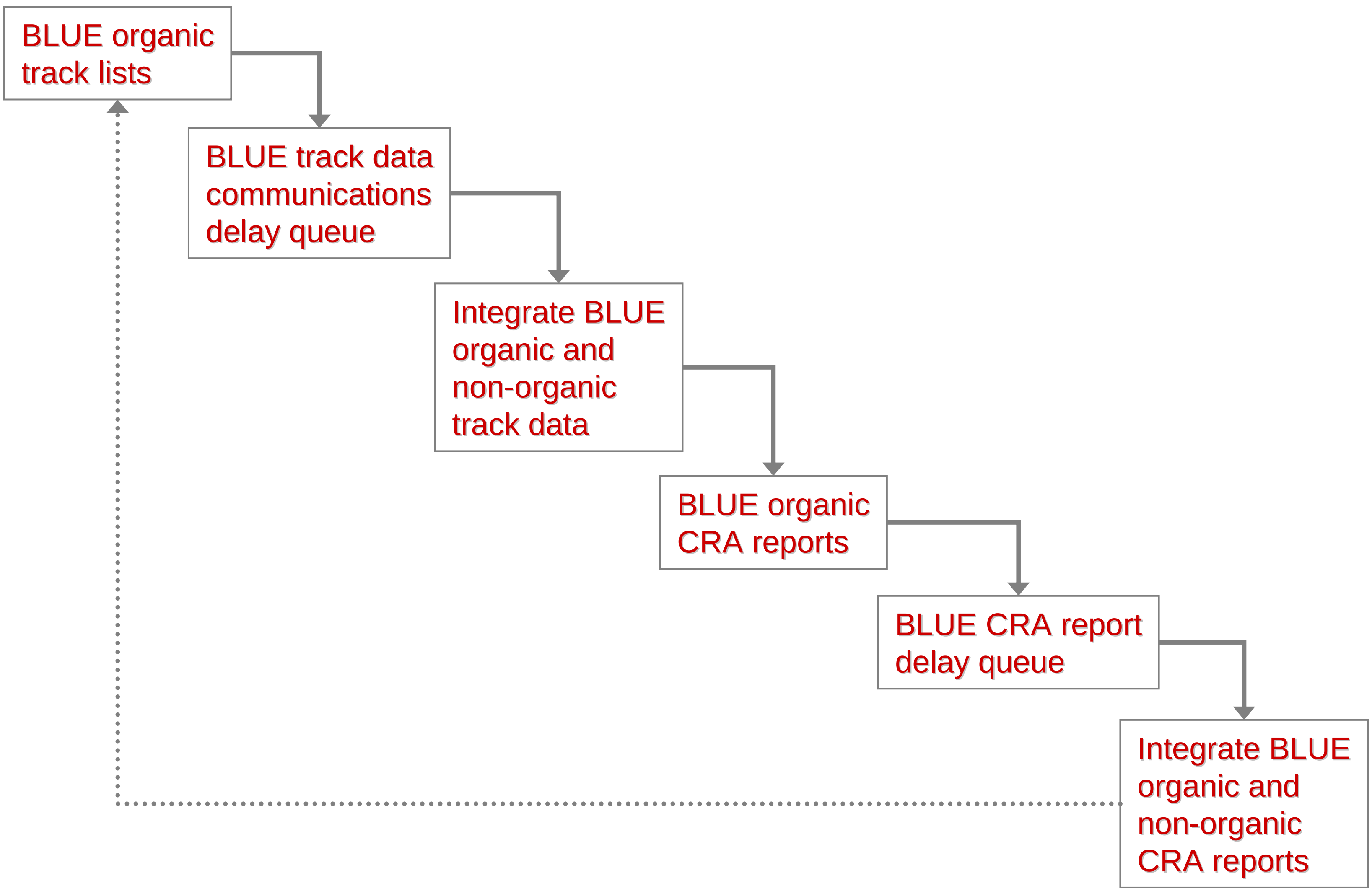
ABM CCID-CRA Model Basics: Two Communicating Blue Nodes (II)

- **A track report has the following syntax:**
  - `[ <track_ID> <a_sens_contrib> <n_sens_contrib> <t_sense_contrib> <sci_flag> ]`
  - Where:
    - `<track_ID>` is "who" number (natural)
    - `<a_sens_contrib>` is Allegiance sensor contribution (float)
    - `<n_sens_contrib>` is Nationality sensor contribution (float)
    - `<t_sense_contrib>` is Type sensor contribution (float)

- **A1 and A2 might produce track reports for object 16 such as:**
  - `[ 16 2.09 2.06 1.48]`
  - `[ 16 0.87 0.25 0.78]`



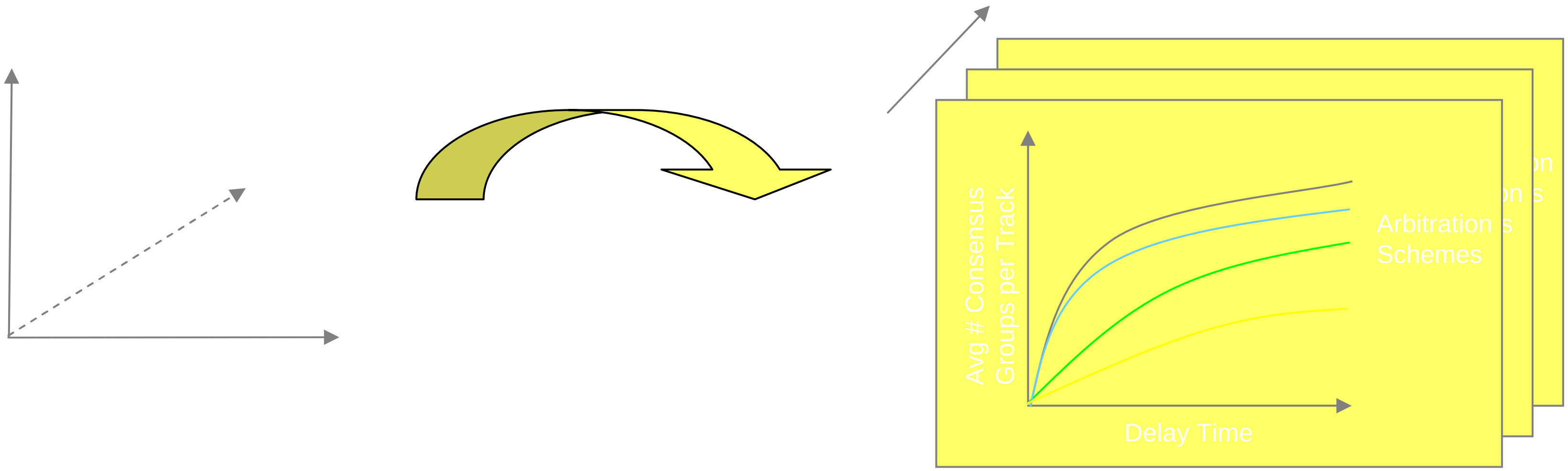
CCID Network Communications Model (IABM model)



ABM CCID-CRA Study

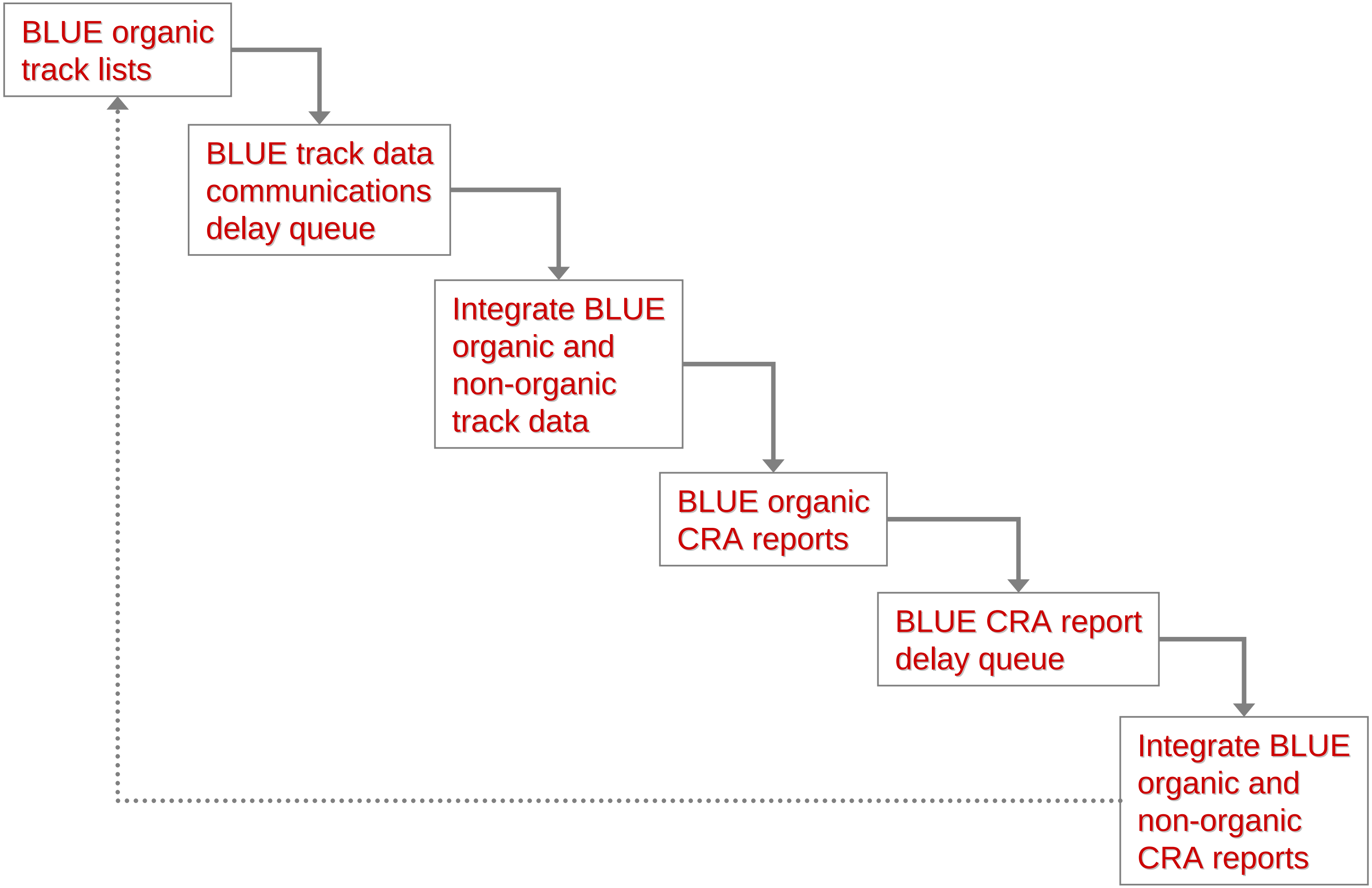
- **Allows rapid examination of various CCID-CRA communications architectures**
  - Dynamic Network Communications and Information Awareness
    - Captures dynamics of real-world network reconfigurations
    - Allows agents (ships) to exhibit new tactics
    - Allows observation and study of emergent behaviors of agents based upon changes within the operating environment (from both internal and external forces)
  - Provides faster, more reliable analysis of dynamic networks
    - Analysis is scenario independent
    - No need to model specific network configurations -- Dynamic network evolves naturally
  - Explicitly models ship awareness and communications links
- **CCID-CRA ABM addresses three questions**
  - What is the best strategy to synchronize (mitigate conflicts) between CRA nodes?
  - How do communication delays affect the overall performance?

ABM Experimentation Plan



- **ABM**
  - Vary number of contacts, maximum delay time, and arbitration scheme
  - Baseline Run
    - Multiple ships operating with no final CRA arbitration
    - Expected results: Excessive number of IDs for the same “ground truth” track
  - Arbitration Scheme Runs
    - Determine best arbitration scheme (based upon lowest average number of consensus groups per track)
    - Expected results: Compared to baseline, lower number of IDs for the same “ground truth” track
  - Overall expectation: Higher communications delays produce more IDs for the same track

CCID Network Communications Model (IABM model)



Constraints and Simulation Needs

- **Constraints**
  - No Existing Operational IABM Architecture
  - No multi-platform CRA baseline exists for comparison purposes
  - CRA source code within LM exists only in a classified environment

- **Simulation Needs**
  - Establish baseline for comparison
  - Multi-tier Simulation
    - Asses unknown factors at different levels of fidelity
  - Capture the effects of communication systems
    - Effects of bandwidth availability (link connectivity)
    - Effects of Transmitted Data Pedigree
      - Ex. Peer-to-Peer connections transmit more info than Link 16
  - Test scalability of proposed multi-platform CRA
  - Ability to test multiple scenarios under varying conditions
  - Capture the effects of the presence of SCI level information

Experimentation Plan (1 of 2)

ABM used to recommend "best" architecture

- **Preliminary Investigation using Agent-Based Models (ABMs)**
  - Enables validation of proposed system architectures
    - Allows experimental validation of an architecture under varying, unforeseen conditions
  - Models Dynamic Network Communications and Information Awareness
    - Captures dynamics of real-world network configurations
    - Allows platforms to execute new ID declaration rules
  - Enables rapid execution of multiple scenarios
  - Explicitly models ship awareness, communication system throughputs
  - Allows for analysis of CRA network architecture (independent, localized, distributed, etc.)
- **Expected Results**
  - Recommends the "best" CRA deployment architecture
  - Provides input to CONOPS
  - Recommends best ID declaration rule(s)

ABM CCID-CRA Model Basics: Model of Time (I)

- **Blue Agents must transmit track reports and CRA reports (based on those tracks) to each other**
- **We assume an “IABM” environment**
  - Platform Sensors are disjoint from IABM comms
  - “Full Mesh” comms are used; no limit on with whom an agent can communicate
    - All blue forces participate in track report *origination*
    - Only blue surface agents participate in track sharing, track fusion, CRA report origination, CRA report sharing, and CRA report arbitration
    - [n(n-1) / 2] links, n = blue surface count
- **Despite IABM we want “some” delay in communications**
  - Model the effect of arbitration on multiple CRA reports for the same track received over time
  - Need a “lightweight” delay model

ABM CCID-CRA Model Basics: Model of Time (II)

- **"Time driven", but no built-in time unit is defined**
  - Model execution occurs in "ticks"
- **One "tick" is one iteration of the model**
  - Of course, finer granularity of time means longer processing
    - Our model has 1 tick = 10s, 5s, 1s, 0.1s
    - OR ticks-per-hour = 360, 720, 3600, 36000, respectively

ABM CCID-CRA Model Basics: CRA Belief Value calculation (I)

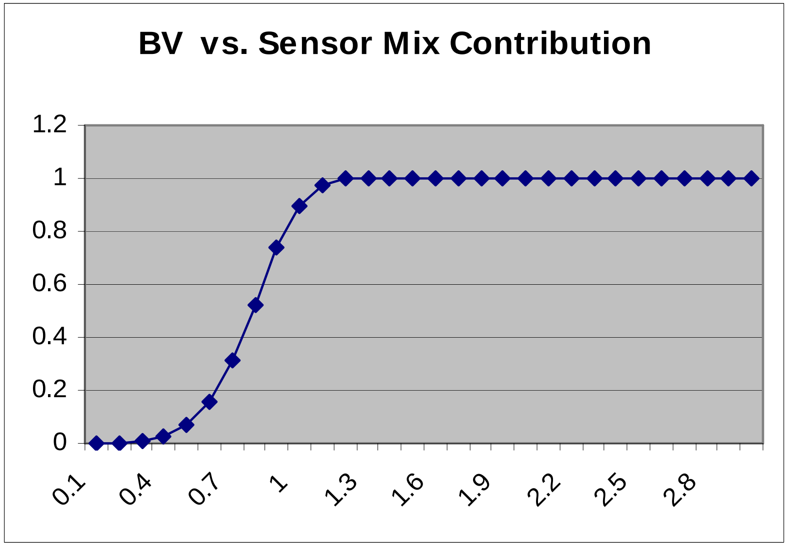
- **A preliminary CRA report has the following syntax:**
  - `[ <track_ID> <allg> <allg_bv> <natl> <natl_bv> <type> <type_bv> <sci_flag> ]`
  - Where:
    - `<track_ID>` is "who" number (natural)
    - `<allg>` is Allegiance recommendation ("enumerated") (similarly for natl = Nationality, and Type)
    - `<allg_bv>` is Allegiance recommendation belief value (float) (similarly for natl = Nationality, and Type)
  - Example:
    - `[3 FOE 0.579 FONAT5 0.7071 DDG 0.5322]`

ABM CCID-CRA Model Basics: CRA Belief Value calculation (II)

- **CRA Belief Value (BV) computation**
  - We needed a lightweight way of having BV = f(sensor mix)
  - BV is supposed to represent probability, so BVs should asymptotically approach 1
  - Sensor mix contributions range:
    - Low end: 0.1
    - High end: 4.4
  - We use the following equation, arrived at by trial-and-error:

$$BV = 1 - e^{-\left(\frac{sensor-mix-contribution}{0.85}\right)^5}$$

  - The curve for this eqn looks like:



Simulation Run Matrices

Run Matrices - Overview

- **Macroscopic parameters set for all runs:**
  - Due to processing time constraints, time granularity of 1 tick = 10s is used (360 ticks / hour of model time)
  - Random seed is fixed at 74
  - One run of each configuration (parameter mix below)
- **Varying parameters:**
  - Agent population mix ("Breed Data")
  - Time Delay: 0s, 10s, 60s, 120s (0, 1, 6, and 12 ticks)
  - Arbitration Scheme ("Majority Voting", "Maximum", "Naïve Bayesian", "Weighted Bayesian")

Metrics

Consensus Group Metrics (I)

- **Average Number of Consensus Groups**
  - At the end of each iteration, the number of consensus groups for each track is tallied
  - These counts are appended to a cumulative global list
  - At the end of the run, the average of this cumulative global list is computed. This is the Average Number of Consensus Groups metric.
  - Example:
    - The global list might typically look like: [2 1 3 2 1 2 2 4 … 3 7 3 6 2 6] (length usually thousands)
    - The average of this list might be “2.78”
- **Note:**
  - For a time delay of 0, the average number of consensus groups is always 1 (i.e. the ideal case).

Consensus Group Metrics (II)

- **Maximum Number of Consensus Groups**
  - We comb the same cumulative global list used to calculate the Average Number of Consensus Groups to find the maximum number therein. This is the Maximum Number of Consensus Groups metric.
  - Example:
    - The global list might typically look like:
      [2 1 3 2 1 2 2 4 … 3 7 3 6 2 6] (length usually thousands)
    - Ignoring what might be hiding in the ellipsis, this run's Maximum Number of Consensus Groups is 7.
- **Notes:**
  - Same geometric comment as for Average applies here

Correctness Metrics (I)

- **Disclaimer**
  - Without the real CRA in play, “correctness” metrics are dubious
  - Much “tweaking” of calculation details was involved
- **At iteration end, each final CRA report is compared to the Ground Truth of the represented track and scored as follows:**
  - Overall correctness:
    - For each CCID attribute correct, the report receives a “1”
    - These sum to the report’s overall score (0 to 3)
    - This score is appended to a global cumulative list:
      [0 0 2 0 1 3 2 2 3 3 3 …]
  - Allegiance, Nationality, and Type:
    - We score a “1” if the attribute is correct, “0” otherwise
    - We append the score to a global cumulative list:
      [0 0 1 0 1 1 1 0 0 1 1 …]
    - One list per CCID attribute

Correctness Metrics (II)

- **End-of-Run Scoring Calculations:**
  - Overall Correctness:
    - The overall correctness for the entire run is computed as:

$$Correctness = \frac{\sum(Score_n)}{3 \cdot n}$$

where $Score_n$ represents values in the cumulative global CRA score list mentioned previously. The "3" in the denominator is there because there are three CCID attributes in a CRA report.

  - Individual CCID Attribute Correctness:
    - Each is similarly computed using the corresponding cumulative global list, in the Allegiance case, for example, as:

$$Correctness_{Allegiance} = \overline{Score_{Allegiance_n}}$$

where the average is over the attribute's cumulative global list.

- **Note:**
  - The correctness metrics just described are reported as percentages

Conclusions

- **There are obvious trade-offs between correctness and the number of consensus groups.**
  - Majority Voting creates the largest number of consensus groups (lends to the most confusion) but has good correctness.
  - Maximum has the lowest number of consensus groups but the worst correctness.
  - Weighted and Naïve Bayesian show both good correctness and good agreement (small number of consensus groups).