Engineering in the Network Dimension to Enhance the Human Dimension – A Framework for Analysis and Design

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Abstract. The way that warfighters share awareness and fight as a team is substantially influenced by choices in networking technologies and interface standards. There is a need for techniques and tools for analysing these choices, to improve Network-Centric Warfare (NCW) systems-of-systems from human-centred design principles. This paper proposes a framework with three features: first, it identifies opportunities for enhanced sharing of situation awareness across warfighters; second, it clarifies the nature of the requisite technologies and systems; and third, it starts to quantify the relative warfighting advantages that should arise. The framework is illustrated by case studies in maritime air defence and naval surface fire support.

Introduction

The Network-Centric Warfare Roadmap (Department of Defence, 2007) is the capstone document for developing the Australian Defence Force (ADF) as a joint and networked force. It draws upon two elements, described as "reinforcing": the Network Dimension and the Human Dimension. The *Network Dimension* centres on the networking infrastructure to connect the ADF's major military systems, while the *Human Dimension* centres on the way that warfighters share their awareness of the situation and hence fight more effectively. The NCW Roadmap then sets target states and milestones for the ADF's NCW capability, and states them in solution-independent terms[1]. However, the artefacts behind the sharing of situation awareness (SSA) may rely on particular networking technologies and interface standards. This creates a risk that the Network and Human Dimensions may not actually be "reinforcing", leaving warfighters to bridge the divide.

This paper is about systems engineering in the Network Dimension to enable and enhance the Human Dimension. The framework is aimed at systems engineers who want to relieve warfighters from the mechanics of SSA, and elevate their SSA to new levels. It can also aid force developers concerned with investment decisions about network infrastructure, as they establish how technologies and systems can achieve advantages in warfighting. For illustration, the paper uses case studies in maritime air defence and naval surface fire support, drawn from work by the Defence Science and Technology Organisation (DSTO).

Background

Systems-of-Systems Engineering for the Australian Defence Force. Previous researchers (Cook, 2001) have argued that the development of the ADF as a system of systems (SoS) requires:

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[1] For example, the NCW Roadmap might provision an aircraft or ship with tactical data links, but does not specify the message set or protocol to be used.

1. Increased influence for top-down planning,
2. A move away from project-centric capability development and,
3. Raised importance of systems characteristics that will enhance integration into SoS.

In Australian Defence, the acquisition of platforms, systems and subsystems (to include networked systems and infrastructure) is driven by a *concept*, a body of thinking about how a collection of systems will operate to achieve some ends[2]. So to support (1), concepts are needed at the whole-of-force level. To strengthen (2), the concepts need to demonstrate a warfighting advantage from the SoS. Finally, to achieve (3) and to go beyond the NCW Roadmap, the concepts need to connect these warfighting advantages to network technologies and interface standards.

Where do concepts come from? Some answers from current practice include:

- Take the current system and upgrade its technologies one-for-one with linear descendants. This "old wine in new bottles" approach can realise quantitative gains (potentially substantial), but qualitative advantages may require new technologies to be matched with new practices.
- Fix the deficiencies in the current system through emerging technology. This "low-hanging fruit" approach could yield immediate and visible benefits, but risks "refighting the last war".
- Field the systems as rapidly as possible and rely on warfighters to find the synergistic combinations. This "learn by doing" approach leverages the adaptivity of warfighters, but cedes the chance to shape the design and implementation of the fielded systems. Warfighters might then have to rediscover issues (potentially while in combat) that could otherwise have been predicted, analysed, addressed through concept development and experimentation.

The above weaknesses in current practice motivate a different approach: analyse future technologies for the functionality that they could provide, and then propose concepts from that functionality. That is, if a technology can carry a particular kind of data, what concepts are feasible? And as future technology expands the quality and quantity of data that can be carried, what are the new warfighting advantages that could be exploited? This paper addresses the gap in techniques and tools for conducting such analysis[3].

Human-Centred Design and Sharing of Situation Awareness. Endsley's model of situation awareness distinguishes the activity of forming situation awareness from its subsequent use in decision-making (Endsley, 2000). Endsley also notes the "huge gap between the tons of data being produced and disseminated and people's ability to find the bits that are needed and process it together with the other bits to arrive at the actual information that is required for their decisions." The issues are magnified in team situations, and invite the application of automation technologies (Cuevas et al, 2007). In targeting Endsley's "huge gap", this paper made two postulates:

1. **Activities for Automation**. Take Endsley as a starting point, and suppose that SSA can be associated with extracting and processing "bits" of data together, systematically and rapidly, to enable decision-making. Then consider the kinds of activities that humans and machines are each best at, as suggested for instance by the Fitts List (Geer, 1981). When put together

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[2] Typically a concept is recorded in an Operational Concept Document, and captured through architecture products, for instance the Department of Defense Architecture Framework (Department of Defense, 2007).

[3] This can be put alternately in terms of *dedicated* and *virtual* SoS (Cook, 2001). *Dedicated* SoS are large complex systems that comprise substantial, large-scale component systems that to a large extent were designed to work together; *Virtual* SoS are formed at short timeframes, in a manner rarely envisaged at the design phase of the individual component systems, and frequently from elements not well designed for integration. A virtual SoS places significant strain on warfighters (the Human Dimension) from having to manually integrate components. A better solution is to establish concepts for how a future force could operate as a dedicated SoS, and use them to drive development and acquisition (the Network Dimension). This paper seeks to enable such analysis.

(Table 1), the result is a prediction that machines are best used to automate SSA, and thus free humans for decision-making[4]. The question is then: How can network technologies and interface standards be characterised with regards to putting "bits" of data together?

2. **Mediating Artefacts and Enabling Technology**. Sharing of situation awareness[5] may rest upon *mediating artefacts* (Hutchins, 1996); for instance, shared displays supporting shared mental models (Bolstad and Endsley, 2000). Implementing the mediating artefacts may require specific choices in technology. In parallel, as emergent technologies enable greater capacity over further distances, extant mediating artefacts could become easier to construct, and new artefacts may well become possible. The question again: how can this be characterised?

Table 1. Fitts List applied to Sharing of Situation Awareness.

	Humans Excel In	**Machines Excel In**
Activities towards Decision-Making	Perceiving patterns and making generalizations about them Storing large amounts of information for long periods, and recalling relevant facts at appropriate moments Exercising judgment where events cannot be completely defined Improvising and adopting flexible procedures Reacting to unexpected low-probability events Applying originality in solving problems (ie alternate solutions) Profiting from experience and altering course of action Reasoning inductively	
Activities towards Sharing of Situation Awareness		Performing routine, repetitive, or very precise operations Storing and recalling large amounts of information in short time periods Performing complex and rapid computation with high accuracy Repeating operations very rapidly, continuously and precisely Operating in environments that are hostile to man or beyond human tolerance Deductive processes
Other Activities	Detecting certain forms of very low energy levels Sensing an extremely wide variety of stimuli Performing fine manipulation, especially where misalignment appears unexpectedly Continuing to perform when overloaded	Monitoring (both men and machines) Responding very quickly to control signals Sensing stimuli beyond the range of human sensitivity (eg infrared, radio waves) Doing many different things at the same time Exerting large amounts of force smoothly and precisely Insensitivity to extraneous factors

[4] Subsequent researchers have moved beyond the Fitts List into the dynamic and adaptive allocation of activities (de Greef et al, 2007), however the prediction still holds.

[5] "Sharing of situation awareness" is taken to include particular forms including "shared", "distributed", "compatible" and "transactive" situation awareness (Stanton et al, 2009). In each of these cases, the central point remains – that there are artefacts that mediate the formation of situation awareness within a team.

A number of researchers have sought principles or requirements for how systems can be designed for SSA (Harris, 2001) (Sonnenwald et al, 2004) (Hayes-Roth, 2006), and systems have been developed for particular applications (Tan et al, 2007) (Risser and Smallman, 2008). Some solutions have sought to use automation to structure or filter the information presented to team members, for instance, through fuzzy cognitive maps (Peruish and McNeese, 2006), semantics and ontologies (Boury-Brisset, 2008), metadata (Loomis et al, 2008). The measurement of SSA has received much attention (Miller and Shattuck, 2006) (Krueger and Banderet, 2007) (Hasan et al 2007) (Campbell et al, 2008) (Salmon et al, 2008), notably how SSA can be supported by technology (Yue et al, 2003) (Schwartz et al, 2008) and that poor choices in technology can impede its formation (Ali, 2006) (Pascoe and Ali, 2006). The research sits alongside the study of human factors that shape SSA (Huber et al, 2007) (Hutchins et al, 2007) (Rosen et al, 2008), and within the characterisation of NCW systems-of-systems; for instance, their architectures (Dekker, 2005) (Nyamekye, 2007), organisation (Sengupta and Jones, 1999) and effectiveness (Parnell et al, 2001) (Perry and Bowden, 2003).

Framework

Sense-Information-Knowledge-Decision-Action with Distance. The goal of this paper is a framework that helps systems engineers to select technologies and standards to support SSA, and hence generate warfighting advantage. The key is to characterise the progression of data from raw "bits" into a form fit for decision-making. An engineer can then map these progressions within their design, and hence locate technologies and standards to fill gaps or realise opportunities.

The foundation is the SIKDA framework (Sense-Information-Knowledge-Decision-Action). The SIKDA framework follows from the Knowledge Analysis Framework (KAF) (Yue et al, 2003), in asserting that that data is obtained from the physical world, and transformed into battlespace actions through ascending levels. The SIKDA framework builds on the KAF by explicitly defining its levels as follows:

- **Sense** (or **Data**) extracts data from the physical environment, and records it in media. An example is the sensing of photons on a charged-coupled device, and hence as a digital image.
- **Information** is a communication about an object. The distinguishing feature of an object is that it can be isolated from the physical world through *parameters*; the transmitter sends parameters, and when decoded, the receiver knows the entity that is being referenced[6]. An example is to parameterise an aircraft as a track number, with location, heading and speed.
- **Knowledge** is a communication about an object's intent. An example is to describe an aircraft as being "friendly" or "hostile".
- **Decision** is a communication of direction. An example is a command to launch a weapon.
- **Actions** are made into the physical environment; for instance, firing a weapon.

SSA and warfighting advantage are then realised through systems within each level, and the end-to-end transformation across levels. If *range* is selected as the measure of superiority, then the result is a SIKDA-D chart (Figure 1). Range is a general characteristic of technologies and subsystems in the Network Dimension; for example:

- A radar has maximum instrumented range, the maximum distance at which a radar will detect a perfect scatterer. Radar range may be reported against a given radar cross section, as targets are rarely perfect scatterers. Radar range will also be shaped by the environment; from terrain, the earth's curvature and atmospheric conditions (Meikle, 2008).

[6] Implicitly, the transmitter and receiver have agreed to a protocol for encoding and decoding parameters.

- A data link has similar issues, in reliably discerning a signal out of noise. Again, this range may fluctuate with environmental conditions.
- A missile's range will be bounded by the fuel it carries and the trajectory that it follows to a target. This can be further reflected in probability of kill values out to a range.

A SIKDA-D chart thus takes the SIKDA levels for vertical axis, and Distance as the horizontal axis. The Distance axis starts from a point to be defended and grows towards the enemy.

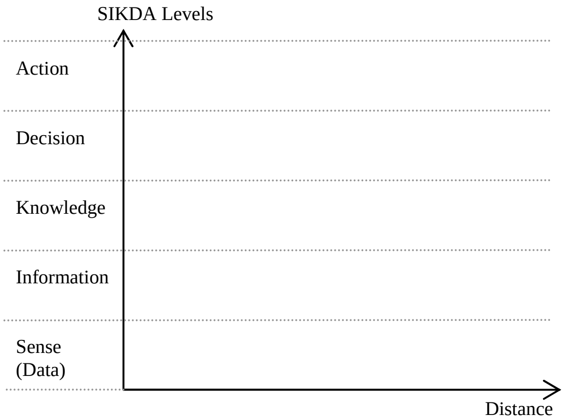


Figure 1. Sense-Information-Knowledge-Decision-Action with Distance (SIKDA-D).

Given an NCW system-of-systems, a SIKDA-D chart is constructed as follows (Figure 2):

1. **Platforms**. Platforms are shown as thin vertical tubes (‖). The horizontal location marks the location where the platform would nominally be deployed. The tube's vertical extent depends upon the systems hosted by the platform, as covered by the next four points.
2. **Sensors**. Sensors are plotted as right-to-left arrows (←) in the Sense level. The arrow's head marks the sensor's location, and its length denotes the sensor's range. A sensor will be hosted by a platform, so the arrow's head will connect to a vertical tube of a Platform. This represents the capacity for a platform to collect data from the physical world, in the direction of the enemy, through one of its sensors.
3. **Weapons**. Weapons are plotted as left-to-right arrows (→) in the Action level. The arrow's tail marks at the weapon's location, and its length denotes the weapon's range. A weapon will be hosted by a platform, so the arrow's tail will connect to a vertical tube of a Platform. This represents the capacity for the platform to engage the enemy through one of its weapons.
4. **Processing**. Processing is plotted as a vertical arrow (↑) between levels. The arrow's tail marks the level from processor's input, and its head marks the level of the processor's output. A processing system will be hosted aboard a platform, so the arrow fills the vertical tube of a Platform. This represents a step in converting data into battlespace effects.
5. **Communications**. Communications are plotted as horizontal arrows (← , →) in the Sense (Data), Information, Knowledge or Decision levels. The arrow's tail marks the transmitter's location, and its length is at most the range of effective reception. A communications system will be hosted aboard a platform, so the arrow's tail will connect to a vertical tube of a Platform. An arrow's head may also connect to a vertical tube of a Platform to represent communications between Platforms.

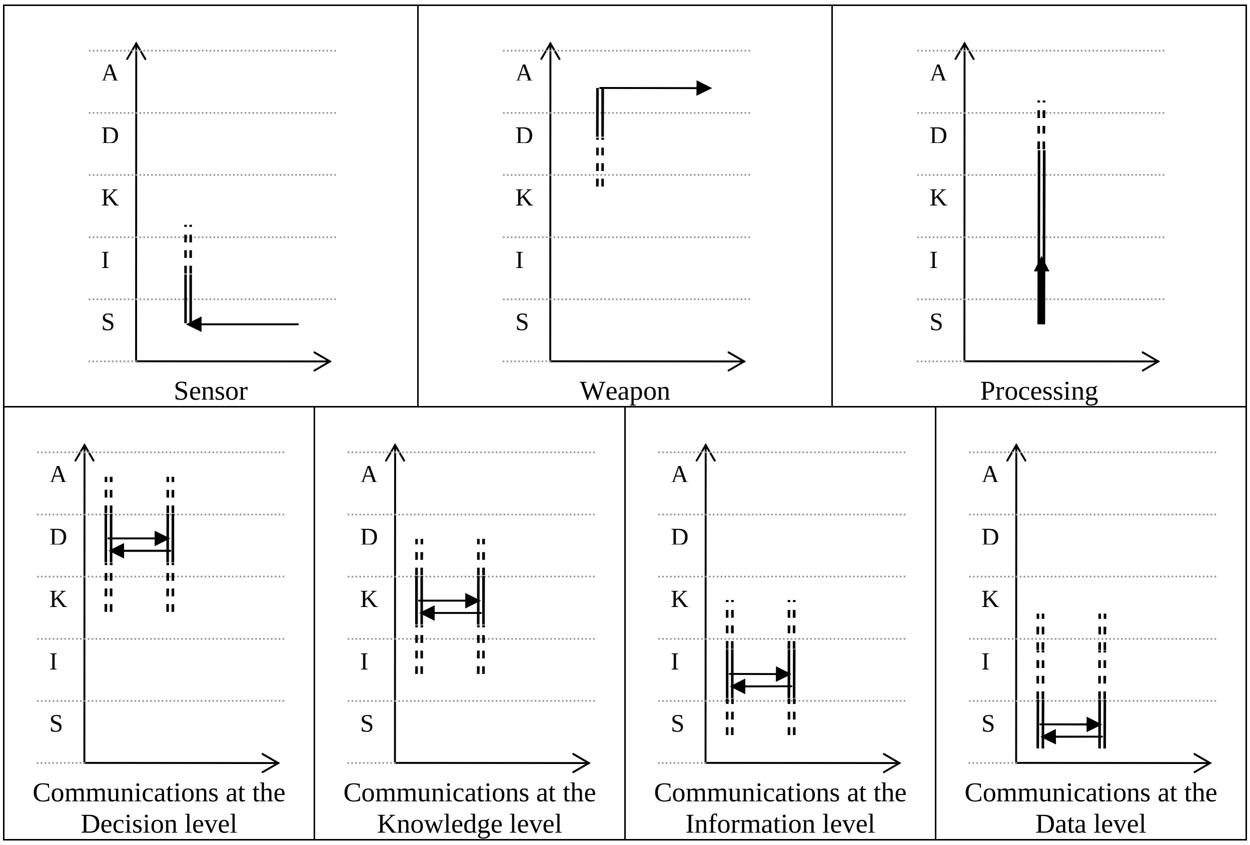


Figure 2. SIKDA-D Schema – Sensors, Weapons, Processing and Communications.

Human Dimension - Communications, Processing and Warfighter Interactions. In a SIKDA-D Chart, communications can occur at the Sense (Data), Information, Knowledge and Decision levels. The levels shape the warfighter interactions; in particular, communications at the Information and Sense levels can lead to elevated SSA, from new mediating artefacts. Historical network technologies have supported communications at the Decision and Knowledge levels, however emerging technologies are supporting real-time, high-capacity networks at the Information and Data levels (Table 2):

Table 2. KAF Levels for Communications Technologies (Examples).

Example Technology	Communications are about …	SIKDA Level
Voice	Commands	Decision
Voice	Situation Reports	Knowledge
Situational Awareness Data Link	Positions	Information
Link 16	Tracks and Coordinates, summarised from what the sensors have detected	Information
Cooperative Engagement Capability	Individual radar detections on a pulse-to-pulse basis	Data
Common Data Link	Signals and imagery intelligence data	Data

Sources: (Beckham, 2007), (Friedman, 2006), (APL Team, 1995), (Jane's, 2008a).

For NCW system developers, Information- and Data- level communications are motivated by:

1. **Reduced loss of data**. To formulate an entity (the Information level), the parameters are extracted from the Data level; all other data is regarded as irrelevant. Processing from Data to Information to Knowledge is thus a compression process, and almost-certainly a lossy one. Compression can serve well when network infrastructure is limited. However, since the compression is lossy, there is a risk that Information relevant to one party may be discarded by another. This could lead to lost insights (in particular, failing to find the enemy). Thus, Data- and Information-level communications have the merit of preserving data for as long as possible, prior to extracting Knowledge.
   Put alternately, the Data, Information and Knowledge levels are in rough correspondence with the Endsley situation awareness Levels 1, 2 and 3 respectively (Endsley, 2000). Data- and Information-level communications then have the merit of strengthening SSA at Levels 1 and 2, as the foundation towards Level 3 and decision-making.
2. **Mediating artefacts for situation awareness**. Technologies at the Knowledge and Information levels can ease the construction of the mediating artefacts behind SSA, or support new artefacts. For example, in historical air-defence systems post World War II (Friedman, 2000-01), an important artefact was the plot of positions and tracks. These were originally plotted by grease pens on plexiglass from verbal reports, a process that operated at the speed of verbal interactions; while interactions were formatted and scripted to reduce ambiguity, their manual nature increased the possibility for error. An Information-level technology was to have the radar report its track to a computer over a tactical data link, to be combined with other track reports into a single display – a Common Operating Picture.
   In contrast, it is impractical for a human to verbally convey every pulse returned by a radar, or every pixel from a live video image. These tasks are, however, readily accomplished over modern and emerging data links (APL Team, 1995), and lead to new mediating artefacts. For example, in historical close-air support, pilots would receive a verbal "talk on" to a target (Brown et al, 2006); the ground controller and pilot could each see the target through eyes and sensors, but had no way of sharing what they saw. A Data-level technology is to stream video to and from the aircraft, giving pilot and ground controller a common view of the target (Jennings, 2008) – that is, enabling imagery to be used as a mediating artefact.

The Network Dimension – Guidelines for Analysis and Design. The following guidelines might be applied to an NCW system of systems, to improve its design:

- **Guideline 1 – Vertically Complete** ("Sensor to Shooter"). Guideline 1 states that there needs to be an unbroken chain of arrows from the Data level, through the Information, Knowledge and Decision levels and into the Action level. Breakages (Figure 3.1) are indicators to incomplete "sensor to shooter" kill chains, with human warfighters having to manually transfer data between systems; such manual transfers are inherently fraught (Hutchins and Timmons, 2007). Guideline 1 is thus an implementation of the Fitts List principle (Geer, 1981) of assigning to machines what machines are good at – in this case, technologies and systems to complete the chains, removing sources of error and improving timeliness.
- **Guideline 2 - Horizontally Matched** ("See First, Shoot First, Win First"). Guideline 2 states that the downrange distance in the Actions layer must be matched or exceeded by downrange distance in the Sensor layer (Figure 3.2). If the distances are mismatched, then the weapons are not being exploited to their potential. By matching and growing these distances, and growing them so that they exceed the enemy's, a warfighter holds the initiative – they can "see first" and "shoot first", at their choice. Guideline 2 is thus a starting point for quantifying a relative warfighting advantage for the networked force.

- **Guideline 3 - Build Ladders** ("Elevate Warfighters"). Guideline 3 states that good concepts will build a "ladder" of communications, ascending through the Data, Information and Knowledge and Decision levels (Figure 3.3). This reflects the earlier discussion on communications, processing and warfighter interactions. Through technologies and systems that cover the mechanics of SSA, Guideline 3 helps to elevate warfighters to new levels.

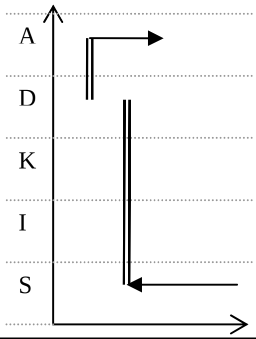
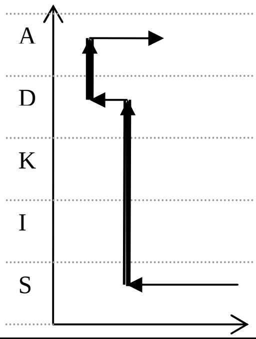
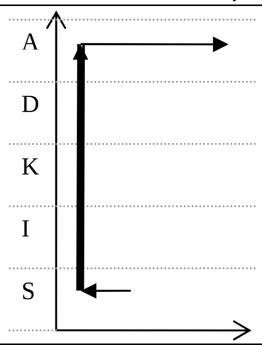
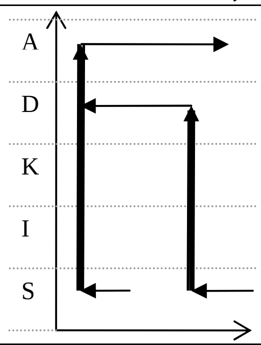
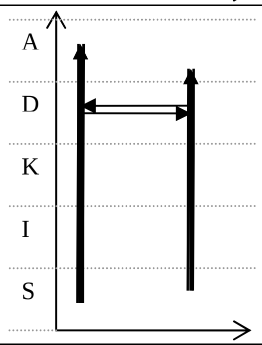
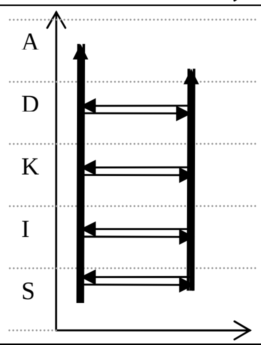
Guideline	If the design looks like …	⇨	seek technologies that yield …
1. *Vertically Complete* ("Sensor to Shooter")		⇨	
2. *Horizontally Matched* ("See First, Shoot First, Win First")		⇨	
3. *Build Ladders* ("Elevate Warfighters")		⇨	

Figure 3. Guidelines for Analysis and Design via SIKDA-D charting.

The design guidelines are based on principles that will be familiar or intuitively understood by warfighters. Principles such as "Sensor to Shooter" or "See First, Shoot First, Win First" are not new. SIKDA-D charts expose how these principles might apply in a design.

Case Studies

The following case studies derive from DSTO research on potential ADF systems of systems (Hew et al, 2006) (Fleming, 2008). They illustrate how SIKDA-D charting and the three design guidelines can be used to elevate the warfighter interactions, leveraging the NCW system of systems to warfighting advantage.

Maritime Air Defence

The first case study concerns the Hobart-class Air Warfare Destroyer (AWD) (Jane's, 2007a) and the Wedgetail Airborne Early Warning & Control (AEW&C) aircraft (Jane's, 2008b) for maritime air defence. It is possible to conceive of weapons for the AWD that can engage further than it can see (Figure 4). Most likely, the AWD will likely have a blind spot below the horizon due to the curvature of the Earth, the so-called *radar horizon* (Kingsley and Quegan, 1999)[7]. A nominal estimate is that, against low-altitude (sea-skimming) targets, the AWD's radar horizon would be at some 30 km[8]. By contrast, a surface-to-air missile such as the SM-6 could have a maximum range exceeding 350 km (Jane's, 2008c).

If the AEW&C is at patrol altitude, its radar horizon can be estimated to be some 230 km[9]. However, the AEW&C is not listed as carrying air-to-air weapons that can reach that distance. Guideline 2 might suggest using the AEW&C to sense beyond the AWD's radar horizon, matching the overall sensor and engagement ranges (Figure 5). Guideline 1 then considers the chain from the AEW&C sensing a target and the launch of a missile. For communications in particular, Guideline 3 invites a number of designs (Figure 6):

- An initial design could implement communications at the Decision and Knowledge levels. An example would be where the AEW&C crew describes what they are seeing on their sensor displays to the AWD crew, and makes recommendations for the AWD to fire a missile. This design could be implemented through voice communications.
- More developed designs could add communications at the Information level. An example would be where the tracks displayed on the AEW&C's displays are copied to the AWD, and vice versa, so that both crews see a consolidated picture of tracks. This design could be implemented using Link 16 (Gonzales et al, 2005).
- Further designs could add communications at the Data level. An example would be where the AEW&C and AWD combine their radar returns on a pulse-by-pulse basis, improving the ability to find and track targets at the edge of the AWD's radar horizon. This design could be implemented using Cooperative Engagement Capability (APL Team, 1995).

When constructed in the 2005 study of amphibious task group operations (Hew, 2006), the SIKDA-D charts clarified what Voice, Link 16 and CEC each had to offer to the AWD – AEW&C combination. It also led to insights about the technologies and systems that the AEW&C might need, in order that the AWD would be confident in launching a weapon from AEW&C cueing.

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[7] A radar horizon can be calculated as $R_{Horizon} \approx \sqrt{\frac{4}{3} R_{Earth} h_{Antenna}}$, with R_{Earth} = 6378 km. This "4/3 Rule" includes a first-order, empirical correction for the atmosphere carrying radio waves around the Earth's curvature.

[8] Take $h_{Antenna}$ = 100 m. This is an upper bound on the height of the AWD's radars above water.

[9] Take $h_{Antenna}$ = 6000 m. The AEW&C may be able to patrol higher (Jane's, 2008c).

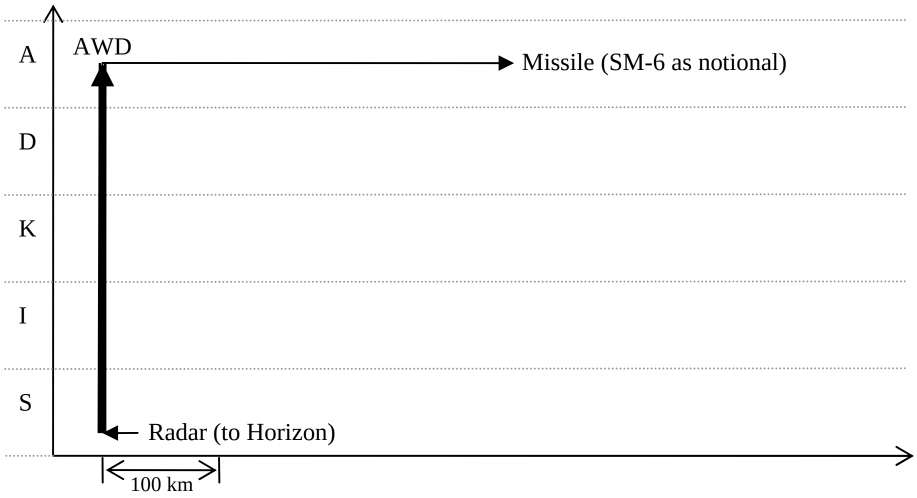

Figure 4. Air Warfare Destroyer – missile range could exceed radar horizon.

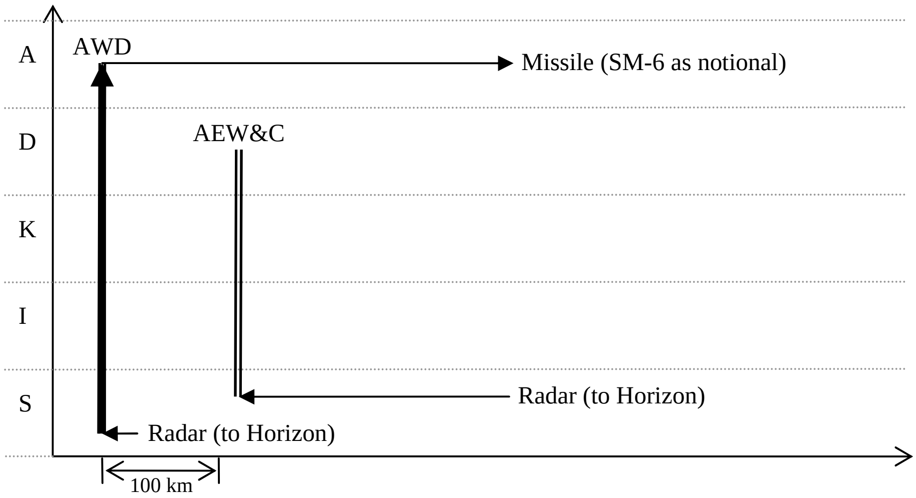

Figure 5. Airborne Early Warning & Control aircraft could extend AWD targeting range.

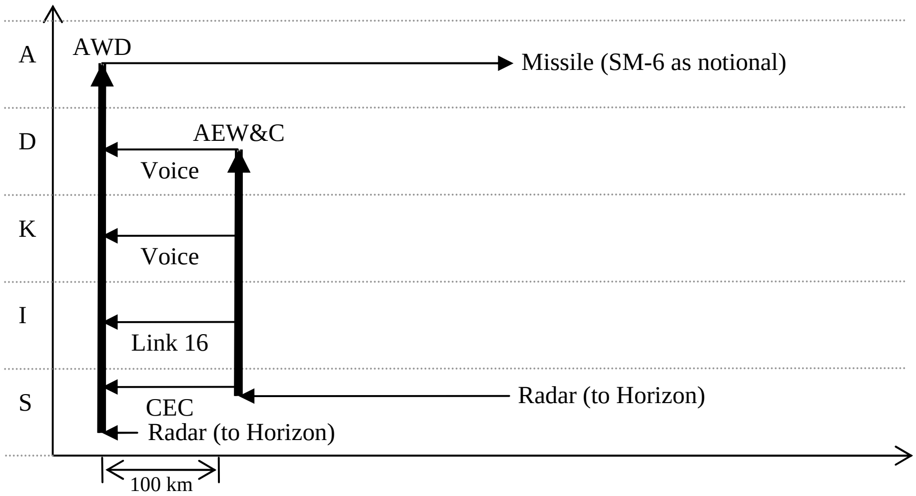

Figure 6. Communications from AEW&C to AWD to cue a missile launch.

Naval Surface Fire Support

The second case study concerns naval fire support to a land unit. In general, the supporting warship will be unable to see that targets that it is firing upon; for example, the Mk 45 gun aboard an ANZAC-class frigate (Jane's, 2007b) has a range of 23 km, but terrain and weather could constrain the frigate's visual range to some 5 km (Figure 7). Under Guideline 2, the land unit might detail a Forward Observer (FO) to call and correct the Frigate's gunfire. Guideline 1 would then look at communications options for doing so (Figure 8):

- An initial design could implement communications at the Decision level. Examples include a FO calling for fire ("Fire mission", "Check fire"), or providing corrections ("Drop 200 and fire for effect"). This design could be implemented through voice technology.
- A more developed design could add communications at the Knowledge and Information levels. An example would be where the FO uses a laser rangefinder and the Global Positioning System to generate coordinates for the Frigate's guns. This design could be implemented using Variable Message Format (Dusseau and Brock, 2003).

A second solution to Guideline 2 is to equip the Frigate with an Unmanned Aerial Vehicle (UAV). Guideline 1 would then consider the communications from UAV to the Frigate (Figure 9):

- The UAV could provide a live video stream. This design operates at the Data level, and could be implemented using Common Data Link (CDL) (Jane's, 2008a).
- Alternatively, the UAV conduct Automated Target Recognition (ATR). Warfighters would then be relieved from having to monitor a continuous video feed, with the UAV handling routine tasks in finding and fixing a target (Hoffman, 2008). This design could still be implemented using CDL, with communications now at the Information level.

Guideline 3 then invites exploration of the communications between UAV and FO (Figure 10)[10]. Importantly, the interactions between the FO and Frigate crew could be elevated to a new mediating artefact, namely the imagery being gathered by the UAV[11]. This design requires the FO to downlink imagery from the UAV, perhaps by a ROVER terminal (Crosby, 2003) (Kurle, 2008).

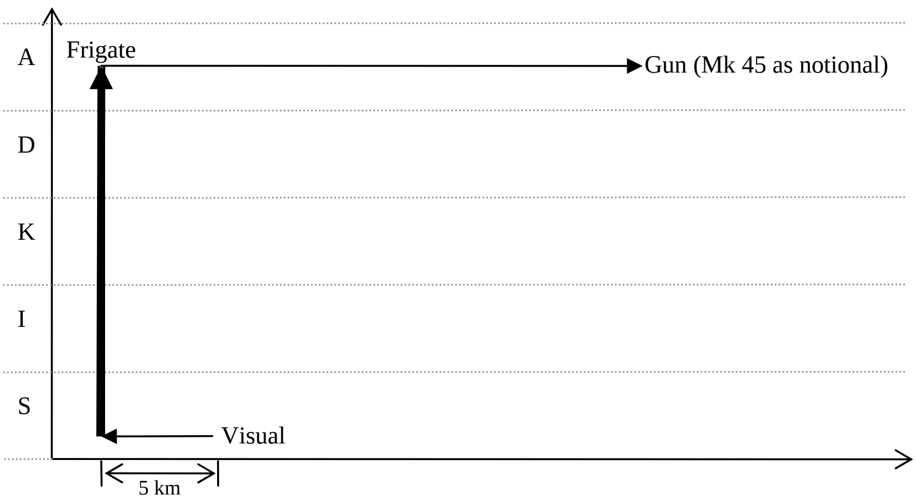

Figure 7. Frigate cannot see to the range of its gun.

[10] For simplicity, Figure 13 omits the Automatic Target Recognition pathway described in Figure 12.
[11] An example would be where the Forward Observer and Frigate crew collaborate to refine aim points, or to deconflict from inhabited areas. They might do so via annotations and overlays, working from the shared imagery.

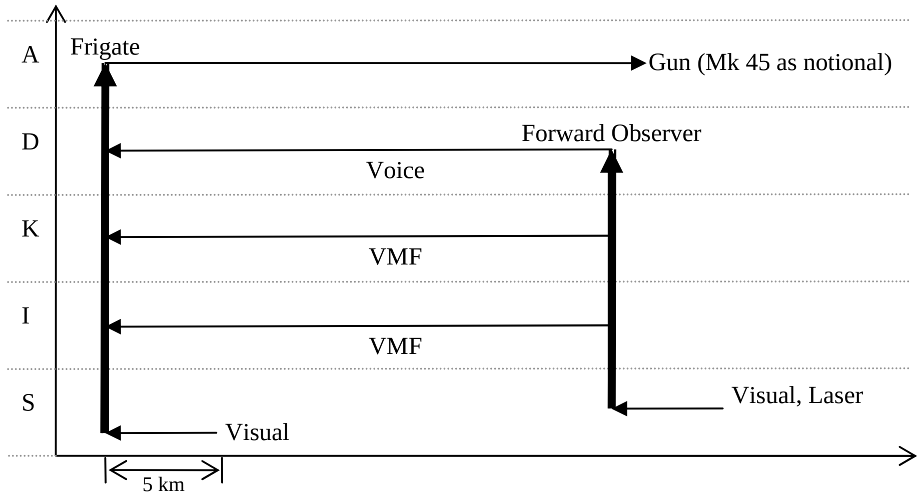

Figure 8. Forward Observer emplaced to direct Frigate's fire.

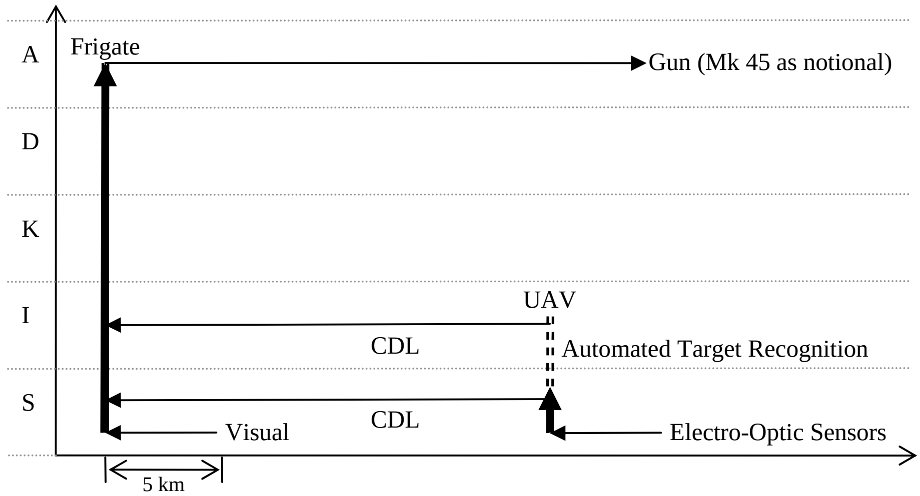

Figure 9. Frigate observes fire through an Unmanned Aerial Vehicle.

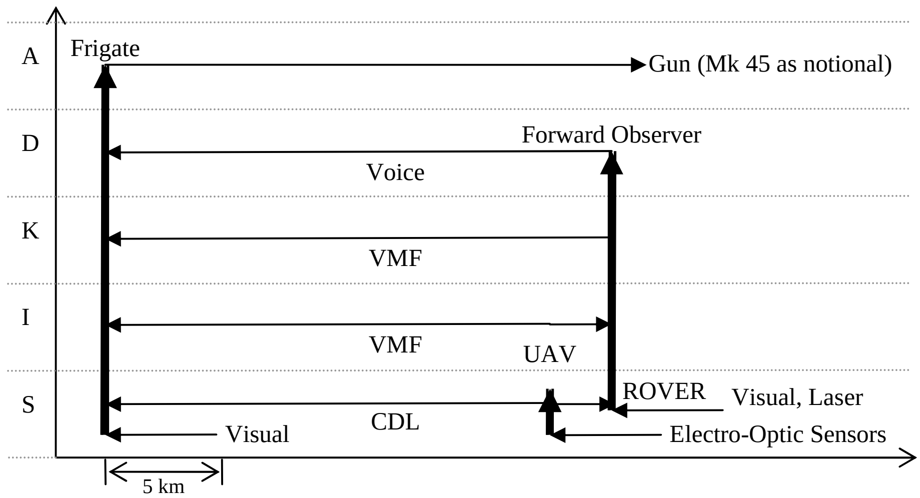

Figure 10. Forward Observer and Frigate share awareness through Imagery.

This case study was constructed from material developed in a 2007 study of imagery in the tactical battlespace (Fleming, 2008). Here, the key value was in helping the DSTO systems engineers to understand what CDL had to offer when compared to VMF, with the SIKDA-D charts carrying patterns and issues across from the 2005 study.

Conclusion

Modern technology offers increasing opportunities to relieve warfighters from the mechanics of sharing situation awareness (SSA), and free them to concentrate on cognition towards decisions. The framework proposed by this paper can locate opportunities for injecting such technologies into a Network-Centric Warfare design, and expose the warfighting advantages that could arise.

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