A NEW SYSTEMS ENGINEERING TOOL (ODIN) FOR EVALUATING AVAILABILITY OF COMPLEX NETWORKED SYSTEMS

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Abstract. With the Singapore Armed Forces (SAF) building up network-centric warfare capabilities, the reliance on the multiplier effects from inter-connectivity and collaborative operations among forces becomes increasingly critical. Availability has been applied typically at the system level, as a means to analyse the readiness and logistics effectiveness of the fighting force. Such a standalone system level Measure of Effectiveness (MOE) is no longer adequate to capture complex interdependency and ensure the readiness of networked systems in a holistic manner.

Today, the Optimised Decisions in Networks (ODIN) tool equips DSTA and the SAF with the ability to quantify networked system architecture and provide the means to identify critical links/bottle-necks that enhance design decision of the architecture. It provides us the means to examine network robustness and survivability under complex threat environment. ODIN seeks to perform resource (spares, manpower, equipment) optimisation at the network or System-of-Systems (SoS) level to ensure they are considered holistically to meet stringent demands. This paper aims to describe the methodologies and capabilities of ODIN. Such Systems Engineering approach could be similarly applied to the design of our smart cities to provide resiliency in design and best allocation of resource to meet the inter-dependencies and high degree of connectivity needed for utilities, transport and communications of today cities.

1 INTRODUCTION

Today modern cities exhibit high level of sophisticated living standards. This requires holistic and integrated urban planning across multiple agencies like utilities, transportation, communication and supporting infrastructure. Basics of water, gas and electricity supply network, efficient public road and rail transportation system, seamless network communication are just some of the essentials of today's smart cities. Ability to achieve such high level of integration requires a top level System-of-Systems (SoS) approach in planning and handling of inter-dependencies amongst the various supporting infrastructure networks to optimise resource allocation, especially in manpower and land scarce Singapore.

In similar fashion, the need for defence systems to be integrated into a System-of-Systems and operate seamlessly across functional and resource constraints is no less demanding. The next generation Singapore Armed Forces (SAF) is seeing revolutionary changes where systems are becoming more inter-connected to leverage the network and information as force multipliers. Planning done at the system (platform) level is no longer adequate to ensure mission success for such network centric operations.

The Optimised Decisions in Networks (ODIN) tool was developed to transform planning to support challenges in network centric operations. ODIN was developed with the ability to simulate complex network topology while incorporating the network systems operational profile, logistics maintenance support concept, system reliability and combat damage modeling. This tool aims to quantify interdependency and interconnectivity across component systems in a networked system. With the means to quantify, ODIN enables one to identify weak links and optimise resource at a network level that ensures mission success for network centric operations.

The Systems Engineering approach and resource optimisation tool described in the paper was developed for the SAF, but is equally applicable and relevant for urban planning of today's smart cities. The complete original article was first published in DSTA Horizons (2014). Singapore: Defence Science and Technology Agency.

2 SYSTEM LEVEL AVAILABILITY

System level availability (Ao) is defined as the average availability of the system out in the field. Take the example of a sensor. Factors that influence the sensor system Ao covers not just the system inputs in terms of reliability and maintainability, but also the operational concept and logistics factors such as maintenance support concept, spares, technician quantity and available maintenance window (see Figure 1). Improving system availability involves not just optimal allocation of spare parts across maintenance agencies but it is also highly dependent on how in particular the sensor is being operated, its inherent system performance and the corresponding supporting maintenance factors.

The above factors can be translated into a quantifiable steady state Ao formula for a system of multiple LRUs indexed by k, k=1,…, k, as shown in the equation below. A Ao of 80% indicates that it is ready for mission on an average of 80 out of 100 hours. Statistically, it can also be interpreted as having an average of 8 out of 10 systems available.

$$Ao = \frac{MTBD}{MTBD + MTTR + WT} = \frac{1}{1 + \frac{MTTR}{MTBD} + EBO} \qquad (1)$$

Where MTBD is the mean time between demand and waiting time, $WT = EBO * MTBD$ is defined by Little's Law.

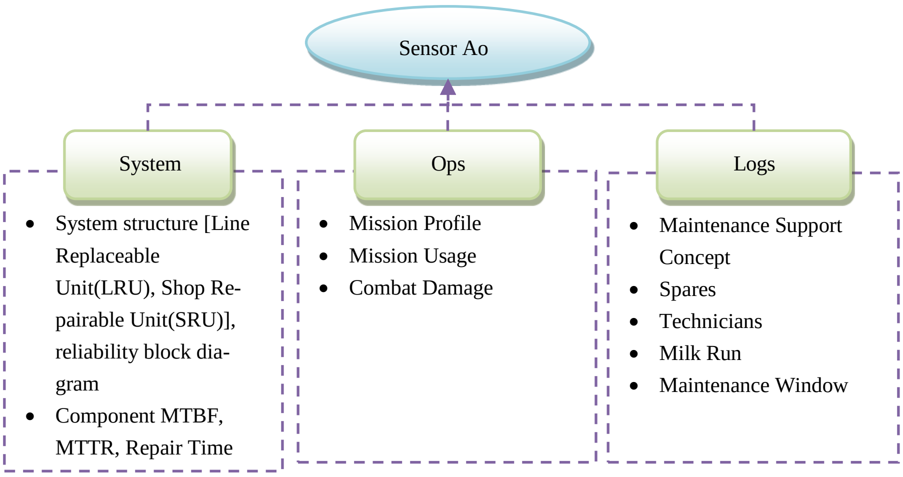


Fig. 1. Factors influencing the sensor availability

A modified version of the formula is proposed as follows (Lau, Song, See and Cheng, 2006):

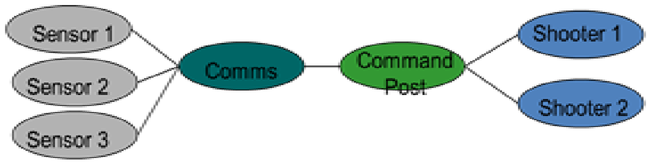
$$Ao = \frac{1}{1 + \sum_k \left(\frac{EBO_k}{N_{sys}} + \frac{UR}{MTBF_k} * QPM_k * MTTR_k \right)} \quad (2)$$

Where EBO_k : Expected backorder of LRU_k;
$MTBF_k$: Mean Time Between Failures of LRU_k;
$MTTR_k$: Mean Time to remove and replace LRU_k;
N_{sys}: Number of system deployed
UR: Utilisation rate of system;
QPM_k: Quantity of LRU_k that the system has;

System level Ao is computed based on the summation across all the LRUs within the system. However, at a networked system level where the end-to-end mission requires collection of systems operating with certain interoperability and interdependency, such standalone system level Ao is no longer adequate.

3 NETWORKED SYSTEM AVAILABILITY

Networked system availability is defined as the availability of the interconnected systems at an end-to-end level. It quantifies the availability of having a link from one point to the other while having to route through the various component systems. Each of the component systems has its individual Ao defined by system level dependency on system, operational and logistics factors shown in Figure 1. Many often argue that such networked Ao can be obtained by simply multiplying them together using analytical formulae. This will derive a quick answer to the simple series-parallel type of networked system shown in Figure 2. However, such a method is very restrictive. First, typical networked systems are often meshed to meet the network redundancy requirements, and it is difficult to formulate the analytical equation. Second, it is not possible to capture the interoperability and interdependency that occur simultaneously across the multiple system types. The largest drawback lies in the analytical formulae multiplying the average of each component system Ao and hence losing the interdependency effect across systems that is the critical basis to the availability of a networked system. In the next section, the limitation of applying system level availability to an increasingly networked system environment is further illustrated.



Ao (Networked System) =

$$[1-(1-Ao_{Sensor\ 1}) * (1-Ao_{Sensor\ 2}) * (1-Ao_{Sensor\ 3})] * Ao_{Comms} * Ao_{CommandPost} * [1-(1-Ao_{Shooter\ 1}) * (1-Ao_{Shooter\ 2})]$$

Where Ao (Networked System): Availability of interconnected system end-to-end;

$Ao_{Sensor\ i}$: Availability of sensor system i;

Ao_{Comms}: Availability of comms system;

$Ao_{CommandPost}$: Availability of Command Post system;

$Ao_{Shooter\ j}$: Availability of Shooter system j

Fig. 2. Analytical computation for simple networked system availability

3.1 Analysing Networked System Availability

Using an integrated system live firing exercise as illustrated in Figure 3, sensors in the form of a Unmanned Aerial Vehicle (UAV) or Artillery Hunting Radar (ARTHUR) are used to conduct battlefield surveillance and detect potential targets. Images of the ground surveillance are sent back to the command post via a communication network that allows the commander to decide on the appropriate strike platforms to take out the adversaries. From the command post, the target positions and information are sent via a communication network to the strike platform, which will engage and ensure the destruction of the acquired targets. It is evident that the mission success of acquiring and destroying the adversary is dependent on the simultaneous working of all systems types inclusive of communications networks. Should any of the systems be down, the mission will fail.

Typically, Ao, spares and resource are evaluated and allocated for each individual system; for example, Ao of 80% for each of the sensor and shooter systems. Such measurement is unable to reflect the interdependency of the various systems across the communication network for the mission. It may also potentially lead to under or over provision of resource and impact the logistical readiness of the systems.

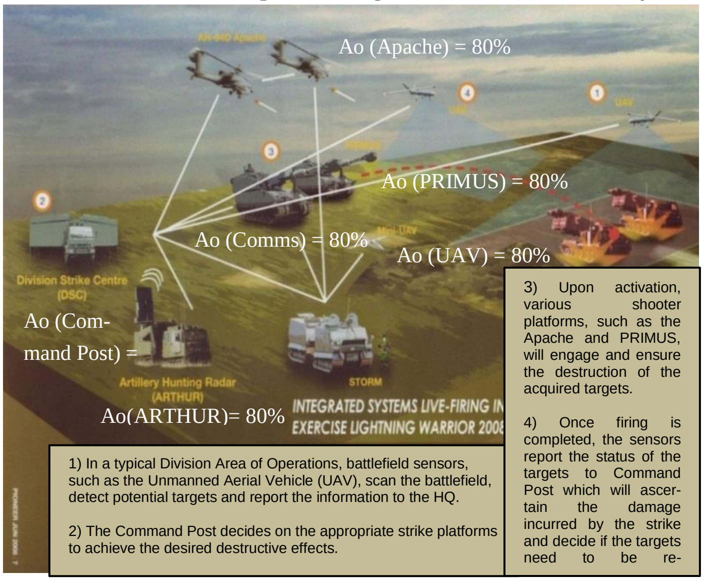


Fig. 3. Integrated systems live-firing exercise

A simplified "acquire & destroy" mission calculation is shown at Figure 4, where ARTHUR is used as the only sensor, PRIMUS (Self Propelled Artillery Gun System) as the weapon system, command post as the command and control centre, and a fixed communication network as the means of information and data transmission. Adopting a standalone system as the criteria for resource or maintenance support planning, the planner would ensure a Ao of about 80% for each of the individual system. However, from the "acquire & destroy" mission definition, it would require all the systems to be functioning together. If the planner's resource planning for each system is at 80% Ao, by simple multiplication the entire networked system is having maximum logistic readiness of only 40%. Therefore resource planning should be carried out at the networked system level. Planners can no longer perform their resource and maintenance support planning by treating each system as a standalone system. With the interdependency among the systems, the Ao of each system may no longer be treated independent of one another. Measurement of the performance of the networked system "acquire & destroy" mission needs to be performed within the model itself.

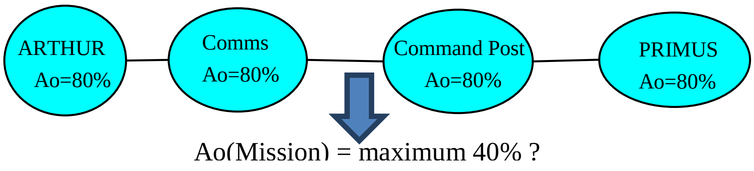


Fig. 4. Simple illustration of Integrated mission Ao computation

4 EXTENDING NETWORK Ao COMPUTATION

With such a complex network structure, system level Ao measurement can no longer suffice as a good Measure of Effectiveness (MOE) as it becomes more dynamic and largely dependent on the context. Two MOEs will first be defined before moving on to illustrate how these MOEs are used.

4.1 Mission Ao / Probability of mission Ao.

Mission Ao will see tighter integration between the operational and logistical contexts. This MOE requires the operational context to define how the operators had intended to interoperate the systems to ensure mission readiness. This mission Ao is highly dynamic and dependent on mission definition.

As illustrated in Figure 4, the mission Ao is defined as the "acquire & destroy" mission. It measures the probability of having sensors acquire the targets and transmitting the information to the appropriate shooters for them to take out the adversaries simultaneously. Mission Ao can also take the form of division to brigade Ao which measures the end-to-end availability from division to brigade by factoring the means for commander to communicate to ensure mission success.

4.2 Matrix of System-to-System Ao.

For a large communication network, single networked system Ao is not representative. Instead, there is a paradigm shift towards the use of upper triangular matrix of multiple source-sink pairs as illustrated in Figure 5. This MOE allows one to evaluate each pair of system-to-system Ao to identify the weak links and bottlenecks at a glance; for example, system-to-system availability of 24 to 58 is low at 22.8% while, system-to-system availability from 51 to 58 is at 73.2%. In addition, system 24 is observed to have low availability to any other systems (first row of matrix), pinpointing to system 24 as one of the key bottleneck.

To Node

From N	24	28	44	45	46	47	48	50	51	52	54
24		11.2%	23.4%	23.6%	23.4%	19.8%	18.4%	19.6%	19.6%	22.0%	20.0%
28			38.6%	38.4%	38.2%	34.0%	33.2%	33.2%	32.8%	36.0%	35.0%
44				92.2%	92.6%	75.2%	73.6%	74.0%	73.8%	78.2%	76.0%
45					92.0%	74.2%	72.6%	73.0%	72.8%	78.0%	75.8%
46						75.8%	74.2%	74.6%	74.4%	79.0%	76.8%
47							89.2%	90.4%	89.6%	74.4%	71.8%
48								89.6%	88.8%	73.6%	71.0%
50									90.0%	73.6%	71.0%
51										73.2%	70.6%
52											92.0%
54											
55											
56											
57											
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62											
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65											
66											

From N	55	56	57	58	59	60	61	62	63	64	65	66
24	22.4%	22.2%	23.0%	22.8%	[illegible]	25.2%	24.2%	23.6%	23.8%	23.2%	23.8%	22.6%
28	37.8%	37.8%	37.8%	[illegible]	[illegible]	42.6%	41.0%	39.6%	40.6%	38.2%	38.6%	38.4%
44	82.0%	80.4%	82.2%	81.8%	81.2%	85.4%	85.4%	85.0%	87.0%	84.8%	84.6%	93.2%
45	82.0%	80.4%	82.2%	81.8%	81.2%	85.8%	85.8%	85.4%	87.4%	84.8%	84.6%	92.6%
46	82.2%	80.6%	82.4%	82.0%	81.4%	85.4%	85.4%	85.0%	87.0%	85.0%	84.8%	93.0%
47	74.0%	72.8%	74.8%	74.6%	73.6%	73.0%	72.6%	73.6%	75.0%	75.6%	76.4%	74.6%
48	72.4%	71.2%	73.2%	73.0%	72.0%	71.4%	71.0%	72.0%	73.4%	74.0%	74.8%	73.0%
50	73.2%	72.0%	74.0%	[illegible]	[illegible]	72.2%	71.8%	72.8%	74.2%	74.8%	75.6%	73.4%
51	72.6%	71.4%	73.4%	73.2%	[illegible]	71.6%	71.2%	72.2%	73.6%	74.2%	75.0%	73.2%
52	82.8%	82.8%	83.6%	83.6%	82.8%	79.0%	78.4%	79.8%	81.2%	84.0%	85.4%	78.6%
54	80.6%	80.6%	81.4%	81.4%	80.6%	76.8%	76.2%	77.6%	79.0%	81.8%	83.2%	76.4%
55		88.4%	90.0%	90.0%	89.0%	83.8%	83.2%	84.4%	86.0%	88.4%	90.0%	82.6%
56			90.4%	90.4%	89.4%	82.2%	81.6%	82.8%	84.4%	87.0%	88.6%	81.0%
57				92.0%	91.0%	84.0%	83.4%	84.6%	86.2%	88.6%	90.2%	82.8%
58					91.0%	83.6%	83.0%	84.2%	85.8%	88.6%	90.2%	82.4%
59						82.6%	82.0%	83.2%	84.8%	87.6%	89.2%	81.8%
60							89.4%	89.2%	91.2%	86.0%	86.2%	85.8%
61								89.4%	91.4%	85.4%	85.6%	85.8%
62									93.2%	86.6%	86.8%	85.4%
63										88.2%	88.4%	87.4%
64											91.8%	85.4%
65												85.2%
66												

Fig. 5. Illustration of the upper triangular matrix tabulation of System-to-System Ao

5 INTRODUCING ODIN

Recognizing the limitations and needs, ODIN was developed to model and evaluate the Ao at a networked system level to reflect the inter-connectivity among systems. Critical links and bottlenecks can hence be easily identified by measuring end-to-end Ao between system nodes. The tool also provides the ability to evaluate the survivability of the network when subjected to combat damage scenarios. In addition, ODIN allows the evaluation of network robustness when subjected to various what-if scenarios; for instance, is the network still able to fulfil its original mission intent when one or two nodes are down?

ODIN provides the capability to optimise the spares and resource at a network level. In this way, resource are no longer allocated uniformly across all systems. Instead, systems found to be the bottleneck or weak links identified from end-to-end evaluation will be allocated higher resource level to better optimise network availability in a more holistic manner. This trade-off ensures that mission readiness can be achieved at the end-to-end level using the most cost effective approach.

5.1 ODIN Methodologies

There have been extensive publications on the performance of network analysis or quantifying resiliency in the context of networks. Research on network reliability quantifies the probability that the network performs its intended function for a specific mission time under known, normal operating conditions (Elsayed, 1996). Other approaches look at quantifying the resilience of the network when subjected to external causes of component failure such as potential catastrophic failures due to attacks, disasters etc (Whitson and Ramirez-Marquez, 2009). Within the ODIN model, measurement of network performance with reliability and probabilistic combat damage (external factors) as failure sources was adopted. Dependencies of the various systems are also looked into to aid in identifying any correlation and weak links.

In a networked system domain, the interaction of the various systems can be viewed as a network with multiple nodes and links. In ODIN, the source node is defined as the origin and the sink node as the destination. For the network, performance is measured in terms of the ability to pass through from the source to the sink without any interruption from any broken links or nodes. Each system is represented as a node and it can be mapped from the source to the sink system with its network Ao measured. Each individual system availability is affected by its inherent system/component reliability, external probabilistic combat damage together with its unique logistical factors (e.g. maintenance support concept, finite resources) while operating together under the networked system concept.

The mission success of a networked system often requires some degree of interoperability among the individual systems which may be physically sited in different network layers. In order to address this concept of operations, multi-layered networks are modelled within the same model through the concept of network mesh and sub-layers. For example, in the "acquire & destroy" mission, by modelling the communication network as a common mesh layer, the interdependency can be modelled without complicating the network and yet achieve the effect of system dependency on the communication network.

With the use of such a network mesh, users are able to model the interaction and interdependency on different network layers within the same model. The run time of the model is significantly reduced as the network mesh provides the means of decomposition of large complex network layers. Each layer can be computed independently and their interdependency merged rather than computing for a huge complex network (see Figure 6). In addition, rule sets that govern unique routing of each of the network layers can be customised and implemented to capture the network performance accurately.

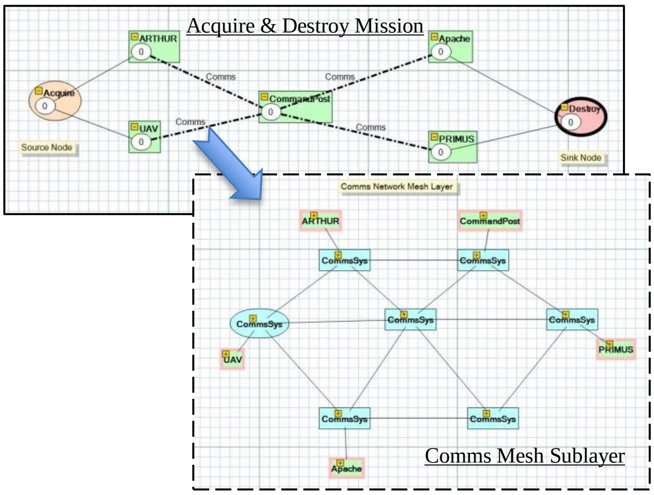

Fig. 6. Illustration of the use of network mesh for modelling the interdependency of different network layers.

5.2 ODIN Tool Architecture

ODIN is made up of numerous libraries and engines, each designed with unique methods and functionalities. Three main engines, namely the process simulation engine, resource optimisation engine and network search computation engine, are integrated to provide the full capabilities of ODIN. The process simulation engine adopts a Monte Carlo simulation method to evaluate the dynamics and stochastic system failures, logistics supply chain, repair process and mission profile. The resource optimisation engine built using mathematical algorithms provides optimum spares recommendation. Finally, the network search computation engine adopts path searching techniques to compute and evaluate the interdependency across networked systems.

Together, they provide a holistic solution to the optimisation of complex networked system availability. A high level architectural view of ODIN is illustrated in Figure 7.

Typically there are two types of failure demand: one arising from component reliability failures and the other due to combat damage as a result of executing a combat mission. The unique nature of each problem type uses different methods in providing a solution in ODIN. Failures in reliability are approximated with mathematical formulation while combat damage failures are approximated via stochastic. For reliability spares optimisation, mathematical formulation - an approximate to Palm's theorem and classical Multi-Echelon Inventory theory (Lau et al., 2006; Sherbrooke 1992; Alfredson, 1997) - is used. The combination of metaheuristic algorithm with Monte Carlo simulation (Dubi, 2000) is adopted for combat damage spares optimisation.

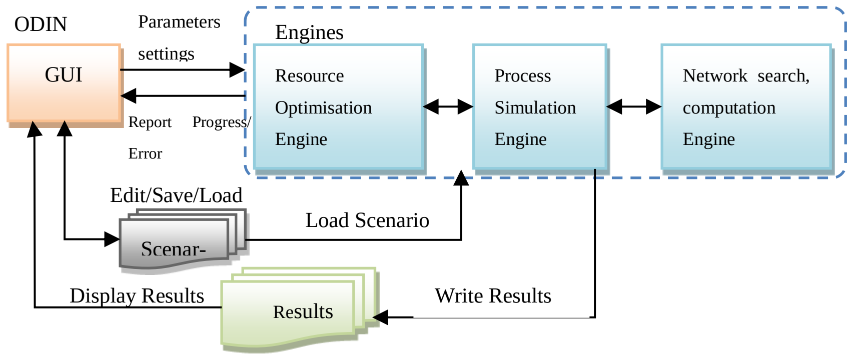

Fig. 7. An Architecture View of ODIN

6 IMPLEMENTATION AND CASE STUDIES

6.1 CASE STUDY 1: NETWORKED SYSTEM ARCHITECTURE EVALUATION

As part of the architectural evaluation of the robustness of the Networked Air Defence design (see Figure 8) in meeting its mission objectives, end-to-end network availability from sensor to C2 (command and control) to shooters was performed. Several key considerations were factored in; for example, sensor network since there was no dedicated sensor-to-shooter pairs. In addition, shooters were dispersed across large geographical locations and linked back to the central C2 system. Moreover, there was the need to handle the IT infrastructure and communication equipments to provide the connectivity among sensor, shooter and C2. Adding to the complication was the different network configurations across different mission phases. All these were modelled through ODIN where multiple network layers were inter-connected and inter-linked to provide end-to-end mission readiness.

Due to the different capabilities of the sensors and shooter in terms of range and threat types, no single mission Ao could be defined. Instead, a matrix of MOE based on the threat and campaign type was used. For example, against threat X, availability was measured from sensor A or B to Shooter I or II. ODIN enabled the mission readiness of Networked Air Defence to be evaluated in totality despite the independent management of individual systems. This ensured robustness in networked system architecture design with respect to connectivity between the component systems. This was achieved through the quantification and identification of weak links and/or vulnerabilities which enabled the optimisation of the Networked Air Defence Ao through improved connectivity configuration and incorporation of system redundancy.

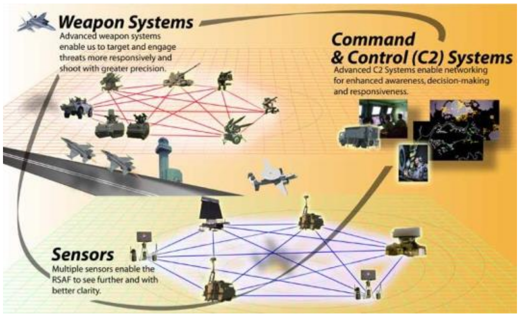

Fig. 8. Evaluation of robustness of Networked Air Defence architecture.

6.2 CASE STUDY 2: NETWORKED SYSTEM RESOURCE OPTIMISATION

A C4 (command, control, communications, and computer systems) system consists of many component systems connected together in a functional relationship. Typically, Ao is measured and resource are catered for at a system or node level. However, it does not provide a commander with a sense of the mission readiness. Hence, this study aimed to evaluate end-to-end network Ao from division to brigade level by piecing together the radios, phones, Command Control Information System (CCIS) to trunk communications equipment. ODIN provided the means to quantify the network Ao down to data versus voice. Such an approach ensured that the spares deployment from different equipments were well balanced with respect to end-to-end availability.

Optimising end-to-end Ao requires tradeoff across multiple factors. For network architecture, it involves deciding between the number of radio links versus the number of radio redundancies available for each system node. There is also tradeoff among the various system configurations as well as the logistics input of spares deployment and support to determine the response to system and network downtime.

With ODIN, the modelling approach takes a step back to look at the fundamental functional level. Instead of the physical series-parallel reliability block diagram modelling, functional routing within and across the systems are modelled so that the system configuration design and differentiation between the voice (V) and data (D) routes can be accurately captured. Figure 9 shows the different possible routing paths to reach end-to-end between the voice (V) to voice (V) and data (D) to data (D) system nodes.

Through such detailed modelling, overall end-to-end network Ao can be optimised globally across various factors including increased client redundancy, improved response time in spares support, review of system configuration design to achieve spares optimisation across systems, as well as operations and logistics at the network level. It involves the levelling of resources across the different component system nodes such as providing identified bottlenecks with higher resources. Results have demonstrated a 10% improvement in overall network Ao. Most importantly, it removes the previous siloed approach which is not only tedious and computationally hard to analyse across the many interacting factors, to today a top level global approach in an automated, elegant and exact solutioning.

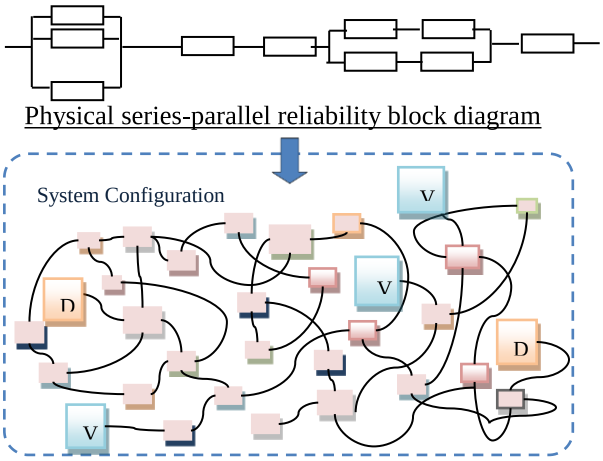

Fig. 9. Illustration of physical series-parallel reliability block diagram modelling versus functional network routes modelling.

7 POTENTIAL APPLICATIONS

Through quantifying the availability of the network, identifying weak links and managing system dependencies, ODIN can be used for the following potential applications:

1. Front-end planning tool in the design of resilient networked system architecture or for network planning;
2. Multi-resource optimisation at networked system level to obtain cost effective solutions while ensuring end-to-end mission readiness.

3. Logistic planning tool to aid the commander in verifying that the logistics plans are able to support operational plans and vice versa.

8 CONCLUSION

ODIN is a Systems Engineering tool that DSTA developed to support own work on complex networked capability design and realization. It equips DSTA with the ability to evaluate end-to-end availability of networked system architecture and captures the inter-connectivity and interdependency across the various systems. It allows one to identify the vulnerabilities and resilience of architecture towards threats. Most importantly, spares and resource optimisation can now be done at a networked system level that results in cost effective solutions to ensure end-to-end mission readiness. Such Systems Engineering approach could be similarly applied for the design of our smart cities. This provide resiliency in design and best allocation of resource to meet the high degree of connectivity and inter-dependencies needs for utilities, transport and communications of today cities.

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