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Measuring Dimensions of Command and Control Using Social Network Analysis: Extending the NATO SAS-050 Model

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Abstract

This paper takes the NATO SAS-050 Approach Space, a widely publicized model of command and control, and gives each of its primary axes a quantitative measure using social network analysis. Deriving such measures means that the actual point in the Approach Space adopted by real-life command and control organizations can be plotted, along with the way in which that point varies over time and function. Part 1 of the paper presents the rationale behind this innovation and how it was subject to verification using theoretical data. Part 2 shows how the enhanced Approach Space was put to use in the context of a large scale military command post exercise. Issues regarding emergent properties and interface bottlenecks were revealed by the analysis, which was further extended to offer quantitative insights into agility and tempo. Above all, the findings show that it was the humans in this particular live NCW situation that granted the levels of agility and tempo that were observed.

Introduction

The NATO SAS-050 Approach Space

In its most generic sense, command and control (C2) is simply the management infrastructure for any large, complex and dynamic resource system (Harris & White, 1987). Central to this paper is the idea that not all management infrastructures are alike and that the NATO SAS-050 Approach Space can be extended to demonstrate this quite clearly.

The NATO SAS-050 Approach Space derives from an underlying information processing view of command and control, in which there is a broadly cyclical pattern of information collection, sense-making and action. This generic C2 'Approach' enabled a comprehensive Reference Model to be developed, comprised of over 300 variables that map onto the C2 Approach. These variables were drawn from fields as diverse as general systems theory, human factors, cognitive psychology and operational research (amongst many others). The 300 variables were then connected by over 3000 links and various systems engineering tools applied in order to undertake a process of 'dimension reduction.' Through this process "three key factors that define the essence of [command and control]" were derived (Alberts & Hayes, 2006, p. 74). These are as follows:

x = allocation of decision rights (from unitary to peer-to-peer),

y = patterns of interaction (from fully hierarchical to fully distributed)

z = distribution of information (from tight control to broad dissemination).

The three key factors form intersecting x, y, and z axes and the three dimensional NATO SAS-050 Approach Space proper (an example is shown in Figure 6). In theory, a command and control organization can be positioned along its respective x, y, and z axes and its position in the Approach Space fixed at any one moment in time. If the values of x, y, and z change then they give rise to successive points in three dimensional space. When linked they form a trajectory, a representation of motion that describes the dynamic behavior of a complex system like NCW. The practice of dimension reduction and the creation of a simple coordinate space into which real-life dynamical systems can be plotted are referred to not as 'Approach Spaces' but as 'phase spaces' (Gleick, 1987). The more extensive the motion within the phase space, the greater the organizations 'variety' is said to be. Variety is a cybernetic principle which refers to the number of different states a complex system can adopt (Ashby, 1956). Rather than 'variety,' the C2 literature (specifically. Alberts and Hayes, 2006) would see this as 'agility' (Alberts & Hayes, 2006).

According to SAS-050 (2007) the two proximal sources of organizational dynamics are function (in that different parts of a command and control organization can be configured differently) and time (configured differently at different points in an evolving situation). Both of these dynamics, in turn, are dictated by the distal source of dynamics represented by the causal texture of the environment or problem that the command and control organization is operating under (and which in turn it is influencing; Emery & Trist, 1978). The NATO SAS-050 Approach Space is therefore joined by a corresponding 'Problem Space.' This too has three dimensions that form intersecting axes and a three dimensional space. These are as follows:

x = familiarity (from high to low),

y = rate of change (from static to dynamic),

z = strength of information position (from strong to weak).

Problems that are merely 'complicated' can be characterized by high familiarity (of underlying principles), non-dynamic rates of change (the situation is stable or else changing at a constant rate) to yield a strong information position. The type of problem to which NCW is a conceptual response is not merely complicated but 'complex.' There are fuzzy boundaries, lots of stakeholders, and lots of constraints often with no clear solution (Rittel & Webber, 1973). Complex problems are in turn characterized by unfamiliarity, change and a weak information position.

The approach and problem spaces are linked so that the area occupied by a putative 'problem' in one needs to be matched by an organization occupying a corresponding area of the 'approach' in the other. In being able to track the dynamic nature of problems the variety and/or agility inherent in the command and control organization matches that of the problem to which it is directed (Bar Yam, 2004; Alberts & Hayes, 2006). This ability to be able to fix and track different aspects of command and control is designed to facilitate exploration of "new, network enabled approaches […] to command and control and compare their characteristics, performance, effectiveness, and agility to traditional approaches to command and control" (SAS-050, 2007, p. 7).

The Missing Links

The NATO SAS-050 Approach Space "is intended to serve as a point of departure for researchers, analysts, and experimenters engaging in C2-related research, conducting analyses of C2 concepts and capabilities, and designing and conducting experiments" (SAS-050, 2007, p. 3). A number of extensions to the model can be legitimately directed into the following three areas.

Firstly, "we are interested in the actual place or region in this [approach] space where an organization operates, not where they think they are or where they formally place themselves" (Alberts &

Hayes, 2006, p. 75). The requirement that flows out of this is for metrics to quantitatively define the position that live command and control organizations adopt on any one of the Approach Space's three axes. If live command and control can be fixed into the Approach Space, then it can be compared 'to traditional approaches to command and control' (or indeed to any other approach). Secondly, the observation that "an organization's location in the C2 approach space usually ranges across both function and time" (p. 76) brings a further requirement to capture and understand the underlying dynamics of NCW. If the underlying dynamics can be captured and understood, then useful aspects of tempo and agility can be revealed. Third, and finally, "identifying the crucial elements of the problem space and matching regions in this space to regions in the C2 approach is a high priority." Fixing and understanding the dynamics of command and control in the Approach Space increases the accuracy of the mapping that can occur between approach and problem.

Part 1 of this paper deals with the innovations that enable these three objectives to be met. Specifically, it describes how the NATO SAS-050 Approach Space (which in its current for is a typological model) can be transformed into a phase space (which is a taxonomic model). An explicit strategy for achieving this is derived from social network analysis and is put to the test with theoretical data. Testing the hybrid social network/NATO SAS-050 Approach Space with live data in Part 2 provides an opportunity to observe the 'what' of NCW, i.e., 'the actual place or region where an organization operates,' how that location varies 'according to function and time,' and whether 'regions in the problem space match regions in the Approach Space.' The aim in this paper is to show how the extended NATO SAS-050 model can help in the formulation of hypotheses as to the 'why' of live-NCW.

Part 1: Developing the NATO SAS-050 Model

Social Network Analysis

At the heart of all the missing links presented above is the ability to provide quantitative metrics that relate meaningfully to decision rights, patterns of interaction and dissemination of information. Social network analysis (SNA) is used to overcome this limitation.

A social network is created by plotting who is communicating with whom on a grid-like matrix. The entries into this grid denote the presence, direction and frequency of a communication link. The matrix can be populated using information drawn from organization charts and standard operating procedures so that it describes where an organization formally places itself. Consistent with the Approach Space is that the matrix can also be populated with live data that describes where an organization is 'actually' placed.

If a social network is "a set of entities and actors [...] who have some type of relationship with one another" (Driskell & Mullen, 2005, p. 58-1) then social network *analysis* is about mathematically scrutinizing those relationships to discern properties that are not necessarily apparent from visual inspection of the network itself (e.g., Harary, 1994). These properties which include several that relate to decision rights, patterns of interaction, and distribution of information.

Decision Rights Mapped to Sociometric Status

Decision rights can be mapped to the social network metric called 'sociometric status,' which is given by the formula:

$$\textit{Sociometric status} = \frac{1}{g-1}\sum_{j=1}^{g}(\chi ji + \chi ij)$$

where g is the total number of agents in the network, i and j are individual agents, and x_{ij} are the number of communications extant between agent i and j (Houghton et al., 2006). Sociometric status gives an indication of the prominence that each agent has within the network in terms of their ability to communicate with others. The hypothesis, therefore, is that unitary networks would generally posses fewer agents with Sociometric status values greater than the mean (corresponding to unitary decision rights) compared to peer-to-peer networks (wherein status should be uniformly higher and more evenly spread).

Patterns of Interaction Mapped to Network Diameter

Patterns of interaction can be mapped to the social network metric 'diameter,' which is given by the formula:

$$\textit{Diameter} = \max_{uy} d(u, v)$$

where d(u, v) is "the largest number of [agents] which must be traversed in order to travel from one [agent] to another when paths which backtrack, detour, or loop are excluded from consideration" (Weisstein, 2008; Harary, 1994). Generally speaking, the bigger the diameter, the more agents there are on lines of communication. The hypothesis is that a peer-to-peer organization facilitates more direct and therefore distributed communication (and thus has a smaller diameter) than a hierarchical network, with more intermediate layers in between sender and receiver (and a higher diameter score).

Distribution of Information Mapped to Network Density

Distribution of information can be mapped to the social network metric 'density,' which is given by the formula:

$$\textit{Network Density} = \frac{2l}{n(n-1)}$$

where l represents the number of links in the social network and n is the number of agents. The value of network density ranges from 0 = no agents connected to any other agents, through to 1 = every agent connected to every other agent (Kakimoto et al., 2006). It is hypothesized that a peer-to-peer organization will be denser than a hierarchical one, meaning that (all things being equal) broader dissemination of information will be rendered possible because there are more direct pathways between sender and receiver.

Testing the Metrics Using Network Archetypes

The supposition that diameter, density, and sociometric status can be used as metrics for decision rights, patterns of interaction, and distribution of information can be tested with reference to several theoretical network archetypes. Four of these are based on early social network research by Bevelas (1948) and Leavitt (1951) who defined the following: the 'Chain,' the 'Y,' the 'Star' and the 'Wheel' (shown in Figure 1). The four archetypes enable a body of empirical evidence concerning their efficacy under different task conditions to be deployed. For example, the problem space might be suggestive of a task context that is complex, with the corresponding fix within the Approach Space being in close proximity to the 'Star' archetype. On the basis of Bevelas and Leavitt's work it is possible to not only make a crude judgment about this particular configuration being less than optimal but to outline more precisely why; e.g., networks exhibiting the properties of a 'Star' often overload the heavily connected high status node(s) in complex situations.

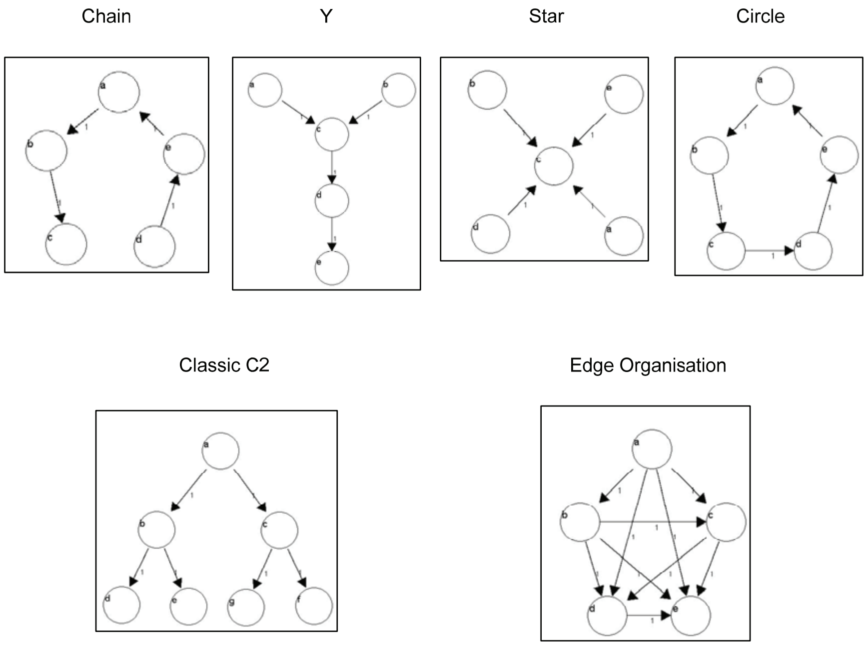

Figure 1. Illustration of archetypal networks. Associated with each is empirical evidence concerning its performance on simple and complex tasks.

Bevelas and Leavitt's archetypes can be joined in the Approach Space by two further network structures derived explicitly from the NATO SAS-050 Approach Space: the 'classic C2' organization and the 'edge organization' (also shown in Figure 6). The Approach Space explicitly represents these archetypes as falling into the bottom left and top right corners respectively. The hypothesis that diameter, density and sociometric status can be used as metrics for decision rights, patterns of interaction and distribution of information can thus be subject to a direct test: if the metrics work as expected, these two network archetypes should occupy positions in the Approach Space predicted by the model.

Reference to Figure 6 shows this to be the case. Using the social network metrics, the classic C2 and edge organization do indeed fall broadly into the areas of the Approach Space predicted. Although classic C2 is not pushed hard into the bottom/left/front position as predicted by the Approach Space, it is positioned in the correct 'octant.' Further investigation of this phenomena reveals hierarchical networks to be much more scale dependent than comparable edge organizations, thus more realistically sized hierarchies do tend to push further into the hypothesized part of the Approach Space (see Walker et al., 2009).

The mapping hypotheses described above is supported: diameter, density, and sociometric status can be used as metrics for decision rights, patterns of interaction, and distribution of information. Using these quantitative measures to plot Bevelas and Leavitt's network archetypes into the Approach Space also helps to fulfill the goal of identifying crucial elements of the approach/problem spaces.

Part 2: Analyzing Live NCW Using the NATO SAS-050 Approach Space

Live NCW Exercise

Having defined a set of social network metrics that map onto the NATO SAS-050 Approach Space, and subjected those metrics to a test with theoretical data, an opportunity now arises to scale up the analysis considerably and to test their efficacy and usefulness with realistically sized 'actual' command and control organizations. This occurs by embedding the approach developed in Part 1 above into a bigger analysis based on a large scale military exercise (see Stanton et al., 2009 for the full analysis). The military exercise in question had the purpose of trialing a digital tactical communications and mission planning system. The current analysis formed part of a wider effort in respect to the following exploratory hypotheses:

Exploratory Hypothesis No. 1: If the human system interaction is regarded as unstable (e.g., Lee, 2001) then people within the system will interpret it, amend it, massage it and make such adjustments as they see fit and/or are able to undertake (Clegg, 2000, p. 467). The exploratory hypothesis concerns what meaningful behaviors emerge that are not anticipated by the designers of the system. The presence of such unexpected behaviors serves as a powerful indication of the type of interaction that users are trying to design for themselves and is thus a useful level of insight, especially within the context of the iterative design cycles necessary to continually evolve NCW systems towards their desired states.

Exploratory Hypothesis No. 2: In the present scenario, concern had been voiced over the efficacy of the digital NCW system's interface. An analysis of communications content (carried out under the rubric of social network analysis) enables the content of communications to be analyzed as well as the relationship between what Endsley (1997) refers to as 'data' (as in simple elements in the environment) vs. 'information' (as in comprehension of what data means for decisions and action). The null hypothesis is that the digital interface should enable similar amounts of data to be turned into information compared to non-digital forms of communications. If an imbalance is detected (the alternative hypothesis) then the possibility arises that the digital system is not facilitating an optimum data/information transformation.

Exploratory Hypothesis No. 3: Echoing the statements of Alberts & Hayes (2006) the interest is firmly directed towards where an NCW organization 'actually' places itself. In the present case the scenario was designed to test a net-centric concept of operations and associated technology. The null hypothesis is that reality and aspiration match. The alternative hypothesis is that due to the adaptations enacted by human users of the NCW system, aspiration and reality mismatch.

Exploratory Hypothesis No. 4: The number of locations that a particular organization is able to adopt within the Approach Space is a reflection of the organization's agility (Alberts & Hayes, 2006; Waldrop, 1992; Ashby, 1956). The null hypothesis accords with Ashby's Law of Requisite Variety in stating that the area occupied by the organization in the Approach Space should match that of the corresponding problem space. The alternative hypothesis is that there is a mismatch in which 'variety destroys variety' (e.g., Ashby, 1956) creating significant difficulties for the NCW organization.

All of these hypotheses are explored with the limiting caveat of a single case study being firmly in place. We are restricted to examining the organization as it exists and without reference to a control condition, however, high levels of ecological validity are assured which permit significant insight into the 'what' of live-NCW. Questions concerning 'why' are the departure points for this work. As it stands, Part 2 of this paper is foremost a test of the extended NATO SAS-050 Approach Space.

Data Collection

Data collection took place at a fully functioning Brigade level headquarters (BDE HQ) set up in a military training area for the purposes of evaluating a particular NCW system. The social network analysis did not focus on all forms of communication. It focused on 'inter-organizational' and 'inter-cellular' communications.

Inter-organizational communications took place between the BDE HQ and geographically dispersed Battlegroup headquarters (BG HQ's). Several of these BG HQ's were simulated, along with enemy forces, from an Experimental Control center (EXCON). This too was geographically disperse from both the live BDE and BG HQ's.

BDE HQ is in itself a reasonably sized organization divided up into the conceptual equivalent of 'departments' (or cells). Inter-cellular communications refer to those that took place between different parts of the BDE HQ as these too placed heavy reliance on the communications capability of the NCW system.

It is important to note that not all communications were able to be captured in this scenario. In particular, it was not practical or feasible to capture inter-personnel communications at a similar level of detail (although wider background to the more informal communications is found in Stanton et al., 2009). This has to be accepted as a limitation of the current analysis.

Aside from that, the Net Enabled command and control infrastructure was set up and staffed as it would have been if deployed. There were a total of 73 active data terminals in the scenario, 17 of which were located in and around the BDE HQ. There were also two encrypted radio sets (and radio operators).

The operations phase took place over the course of a single day (with plans and so forth being prepared the day previously) and took four hours and twenty minutes to complete. In broad terms it was comprised of a rapidly approaching enemy from the West who had to be steered, through a combination of turn and block effects, to the North East of the Area Of Operations into a location where a 'destroy' effect would be deployed. Any remaining enemy units would then continue into the next area of operations which was not under the control of the present BDE HQ. It is important to note that the scenario was not a test of the military effectiveness of the military unit itself, and that the simulated enemy was also rather more compliant than perhaps is normally the case.

Data Sources

Two sources of data were used to inform the analysis. Firstly, comprehensive telemetry was extracted from the NCW system. The sampling rate of the telemetry varied but reached a maximum of approximately 10Hz and yielded a total of 2866 data points pertaining to who was communicating to whom, as well as the broad category of 'what' was being communicated. This 'system log' data presented itself to the user through the NCW system's data terminals and is labeled herein as the 'digital function.'

The second source of data was voice communications which were transmitted over encrypted radio. Data collection relied on a formal log of those communications kept by the incumbent of the Watch Keeper role. Every communication, its time, from who it derived and to whom it was directed, and its content, was recorded and this formed the basis of an analysis of inter-organizational 'voice' comms. Although mediated by a digital radio technology the presenting modality of the communication, from the users point of view, was 'voice' and herein is referred to as the 'voice function.' A total of 158 discreet events of this type were extracted. Both types of data (digital and voice) were supplemented by direct observation of the live scenario and in depth critique from subject matter experts, this analysis being described in full within Stanton et al. (2009).

Modeling

Communications Content: The frequency of transmit and receive events was considered first, followed by a slightly more detailed breakdown of comms. content. On the digital comms. function the system logs already provided a comms. 'type' label and this was preserved and subsequently interpreted in the analysis. The voice comms. function required a different encoding taxonomy and this was derived from

Bowers et al. (1998). Seven communications typologies are defined, with every instance of an inter-organizational verbal exchange being categorized as either:

- Factual: "objective statement involving verbalized readily observable realities of the environment, representing 'ground truth.'"
- Meta-query: "request to repeat or confirm previous communication."
- Response: "statement conveying more than one bit of information" (i.e., comprising of more than simply 'yes/no').
- Query: "direct or indirect task-related question."
- Action: "statement requiring team member to perform a specific action."
- Acknowledgement: "one bit statement following another statement (e.g., "yes," "no")."
- Judgment: "sharing of information based on subjective interpretation of the situation" (Cuevas et al., 2006, p. 3-4).

'Data' vs. 'Information': With two distinct categorization schemes across digital and voice comms. functions, a way to compare across them is required. For this a cautious distinction between 'data' and 'information' is made. Caution is exercised because theoretically these terms remain contentious. As a result, nothing more than a crude attempt to impose this categorization is made currently, and even then it is intended that 'data' and 'information' serve merely as broad descriptive labels. A tolerable stab at defining these terms is made by anchoring them to Endsley's three stage model of SA (1988).

Endsley (1997) points out that success in something like the BDE HQ's endeavors "involves far more than having a lot of data. It requires that the data be transformed into the required information in a timely manner," furthermore, creating information from data is complicated by the fact that what is truly "information" is largely subjective (p.2). In defining these terms we turn to Endsley's model of Situational Awareness (SA). Here, Level 1 SA refers to "the perception of elements in the environment," emphasis being given to 'elements in the environment.' These we might refer to simply as 'data,' that is, as objective, measurable realities of a situation. Level 2 SA refers to comprehension of what those elements might mean whilst Level 3 SA refers to 'projecting their status into the near future' (in other words, actually doing something with the information). Grouped together, Level 2 and 3 SA seem to bound a category that is undoubtedly more 'information-like' than it is 'data-like' (or Level 1 SA-like).

Populating the NATO SAS-050 Approach Space: The digital and voice data were kept separate throughout the analysis as this of course provides an opportunity to see how the organization varied across function. To see how it varied over time, the data was divided into blocks of 85 comms. events and entered into a proprietary software tool called WESTT (Workload, Error, Situation awareness, Tasks and Time; Houghton et al., 2006 & 2007). This tool enabled social networks to be created for each block of comms. events.

Over the course of the four hour and twenty minute exercise period the digital comms. data amounted to 34 blocks of 85 communication events. The voice comms. data was then spread across the same 34 blocks, but being less numerous did not fill the full 85 discrete comms. events per block that the digital comms. achieved. Indeed, no voice comms. events at all took place within the first and last data blocks, so in the case of voice comms. just 32 social network analyses were produced.

Associated with each of the social network diagram is an accompanying density, diameter and centrality metric. The social network metric data was split into 50th percentiles to create a 2 x 2 x 2 taxonomy of: diameter = distributed vs. hierarchical, density = broad/ vs. tight, and status = unitary vs. peer-to-peer (see Table 6 for an example). The 50th percentile containing the greatest number of data blocks represented the modal or static social network achieved in the respective digital and voice functions. In other words, it represents the organization's center of gravity, a time independent characterization of the organization's fundamental mode of operation. The center of gravity for the various network archetypes was also computed using the WESTT software tool in order to facilitate a comparison between live data and theoretical data.

Dynamic Network Modeling: The organization's movement about its center of gravity was visualized by using each of the 32 (voice function) or 34 (digital function) social networks to plot the organization into the Approach Space. By these means it was possible to see how its location varied across time (with each data block representing a time interval) and function (voice vs. digital layers). The range of values that density, diameter, and high status nodes describe over time say something about the organization's agility. When these same values are each plotted onto a graph with the x-axis representing time and the y-axis representing the corresponding social network metric value, the resultant line resembles a waveform. Spectral analysis methods can then be deployed in order to say something about 'tempo.'

Spectral analysis methods, broadly speaking, decompose the time-series data into frequency components using Fourier Analysis. The principle is that complex waveforms can be separated into their component sine (or pure) waves and the resultant data plotted into a graph called a periodogram. A periodogram has a frequency scale on the x-axis measured in Hertz (or cycles per second). As well as speed of fluctuation there is also the strength of that fluctuation, which is ascribed a power value on the y-axis. The measurement intervals used in the current analysis distort the frequency scale somewhat (the sampling rate is not in cycles per second) which means that it is not safe to interpret the x-axis of the periodogram's that follow literally but rather to interpret them 'relatively' in the context of an 'order of magnitude' form of analysis.

With this caveat in place, the periodogram represents an excellent diagnostic tool in terms of it being able to detect the presence of meaningful temporal patterns in the way that the organization configures and re-configures itself under real-life dynamic conditions. If meaningful patterns exist then something of their character can be revealed: evidence of periodicity indicates that the organization is repeatedly drawn into specific locations of the Approach Space (as a fixed attractor in phase space draws physical systems into defined equilibrium states). The lack of a pattern or periodicity is just as interesting. It suggests that the forces present in the problem space which are driving the organization's dynamic reconfigurations are more chaotic in nature (referred to as 'strange attractors' in complex systems terms).

Noise Reduction: A final point is made by Dekker (2001; 2002) that Social Network Analysis, as is common in the social sciences, often contains a significant element of random noise. Steps have to be taken to provide a measure of reassurance that the effects being observed are robust rather than an attribute of random error. To this end the spectral analysis technique just mentioned is combined elsewhere in the analysis with various inferential statistics, the aim in both cases is to go beyond mere description and to try and draw out potentially meaningful patterns in the data.

To sum up the analysis approach: firstly, the raw communications data is split into digital and voice functions. Secondly, each function was then subject to its own form of communications content analysis. Thirdly, the comparison between digital and voice functions was facilitated by a generic data vs. information categorization. Fourth, the organizational center of gravity for both digital and voice functions was derived followed by, fifth, splitting the data into blocks in order to plot the dynamic behavior of the organization in the Approach Space in order to analyze its agility. Sixth, and finally, the time-varying data was deployed further in order to perform a spectral analysis of tempo. This six step process of data analysis enables all of the exploratory hypotheses and the 'what' of live-NCW to be examined.

Results: Content of Communications

Digital Function

2866 individual digital comms. events took place over the course of the 4 hour 20 minute exercise. This equates to a mean of 662 comms. per hour (or approximately 11 per minute). Of those 2866 events, 454 were transmissions (i.e., data leaving the BDE headquarters) and 2412 were receive events (i.e., data entering the BDE headquarters). In percentage terms only 16% of digital communications were transmissions compared to 84% of receive events. Statistical assessment of this disparity allows us to accept the hypothesis that this is a non-random effect ($p > 0.0001$, two-tailed): digital comms. are predominantly 'received' rather than transmitted.

The following pie charts break down the type of communications further in order to examine its content in more detail. Figure 2 shows the content of what is being transmitted based on the descriptive label provided by the System Logs that generated the data.

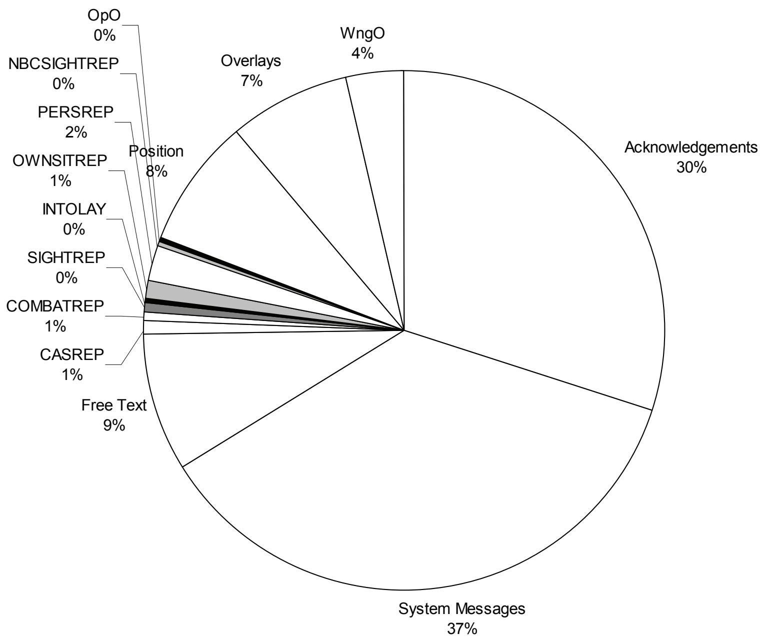

Figure 2. Pie chart showing the' type' of data comms. being transmitted (note that 0% indicates a percentage of less than 1 and that narrow segments have been shaded for legibility).

The largest proportion of transmissions is accounted for by System Messages. These relate to the system's status and current activity (37%). This is followed by acknowledgements that something has been received, or of an action that has been performed on the system (30%). Next in line, and perhaps most interesting in the present context, is FreeText (9%). FreeText, as the name implies, is the facility for users to type messages without the imposition of any kind of pre-determined layout, format or proforma. It is a catch-all form of functionality which, given the level of structured interaction provided by the system, is not one that the designers seemed to anticipate being used all that extensively. In practice, however, it seems clear that personnel rely on it to a far greater extent than expected.

Further Binomial tests demonstrate a persuasive non random effect when FreeText is compared to various other forms of 'constrained text' (i.e., communications in the digital domain that are constrained by templates, pre-defined formats and so on). Table 1 presents the results of this comparison.

Table 1. Free vs. 'Constrained' Digital Comms. that are 'Transmitted'

	N	**Observed Proportions**		
FreeText	39	Constrained	FreeText	Exact Sig (2-Tailed)
CASREP	4	0.09	0.91	$p<0.0001$
COMBATREP	3	0.07	0.93	$p<0.0001$
SIGHTREP	2	0.05	0.95	$p<0.0001$
INTOLAY	2	0.05	0.95	$p<0.0001$
OWNSITREP	4	0.09	0.91	$p<0.0001$
PERSREP	11	0.22	0.78	$p<0.0001$
NBCSIGHTREP	1	0.03	0.98	$p<0.0001$
OpO	1	0.03	0.98	$p<0.0001$

Table 1 shows that the proportion of FreeText comms. is statistically greater than any other individual form of constrained communication. This represents an emergent form of system behavior, one not anticipated by the designers of the present scenario, nor by the designers of the system.

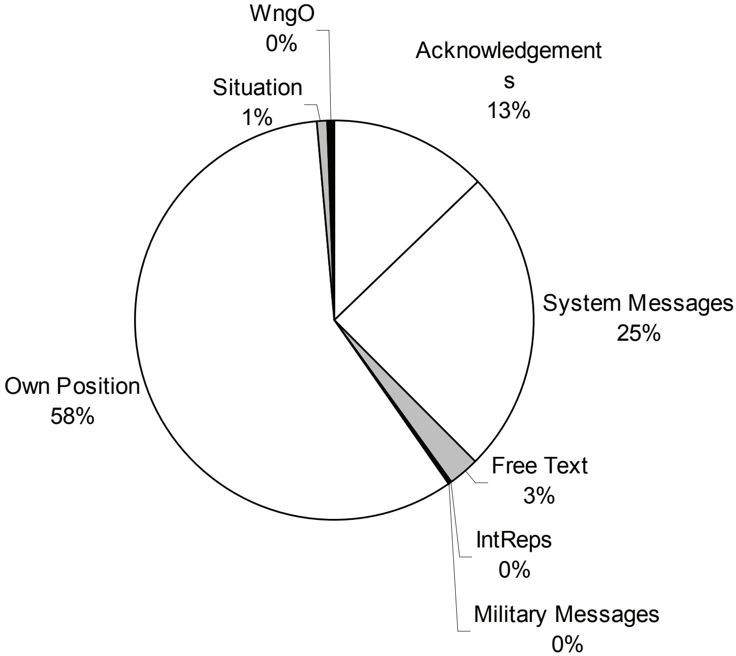

Figure 3. Pie chart showing the type of data comms. received (note that 0% indicates a percentage of less than 1 and that narrow segments have been shaded for legibility).

Moving from comms. transmitted to those that were received (n = 2412), Figure 3 breaks down these events into their content where it is clear that they differ considerably in character from those that are transmitted. By far the largest proportion of incoming digital comms. is accounted for by positional data broadcast by sub-units (58%). Note that the system uses this data to display icons on a digital map display. This is followed by System messages (25%) and acknowledgements (13%). It is interesting to note again the prominence of FreeText. Albeit representing only 3% of total comms, it is fourth highest proportionately. More importantly, FreeText accounts for a greater proportion of comms. than do the more constrained forms of comms. on offer, as Table 2 shows.

Table 2. Free vs. 'Constrained' Data Comms. that are 'Received'

	N	Observed Proportions		
FreeText	65	Constrained	FreeText	Exact Sig (2-Tailed)
INTREPS	4	0.03	0.97	p<0.0001
Military Messages	3	0.06	0.94	p<0.0001
WngO	2	0.16	0.84	p<0.0001

These findings indicate that the quantity and content of digital communications vary considerably with their direction. Broadly speaking, by looking at the two biggest categories, positional data is received whilst acknowledgements are sent/transmitted. Perhaps the most interesting finding is the reliance placed on the FreeText facility. Exploratory hypothesis No. 1 finds support in that this seems to have emerged as a product of user adaptation and contrary to how the system was expected to be used. It serves as an indication of the kind of interaction that users were trying to design for themselves, where evidently they prefer a much less constrained form of interaction than is currently on offer.

Voice Function

Data for the voice comms. analysis is derived from the Watch Keeper's log, a formal record of incoming and outgoing radio comms. A total of 158 communications events occurred over the exercise period which equates to a mean of 36 voice comms. instances per hour (or approximately one every two minutes). As is the case for digital comms., there is a marked disparity in the number of transmissions ($n = 45$) vs. receive events ($n = 113$). Applying the same Binomial test procedure leads us to accept the hypothesis that this disparity did not arise merely as a product of random error alone ($p < 0.0001$, two-tailed). A categorization for the voice comms. data is derived from Bowers et al. (1998). The results of this categorization are shown in Figure 4 (for transmit events) and Figure 5 (for receive events).

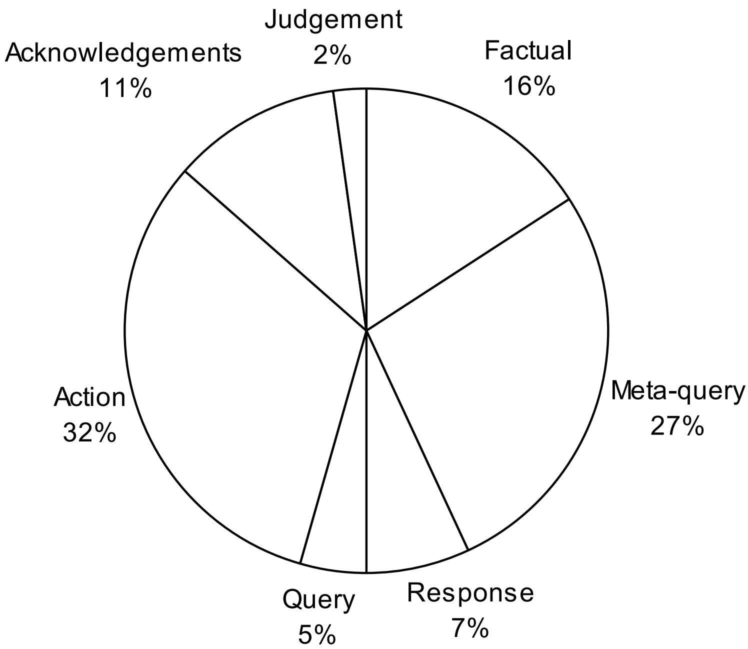

Figure 4. Pie chart showing the content of voice comms. transmitted according to Bowers et al.'s (1998) taxonomy.

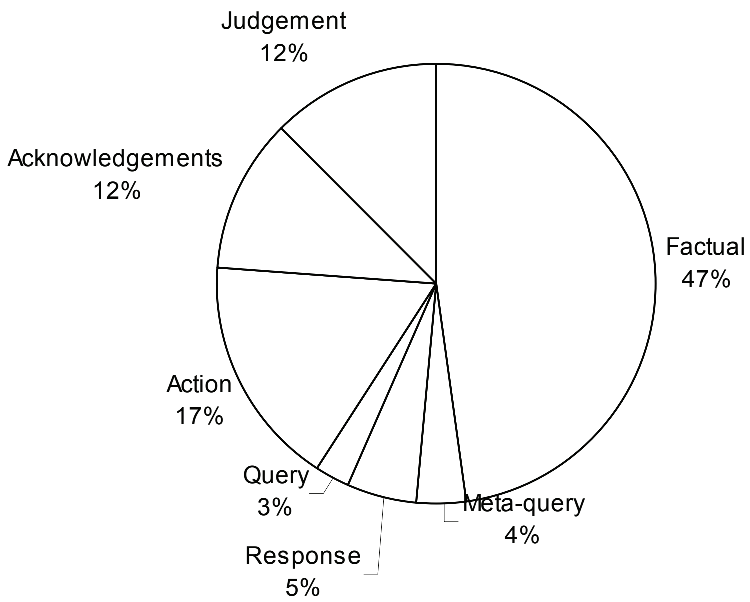

Figure 5. Pie chart showing the type of voice comms. received according to Bowers et al.'s (1998) taxonomy.

The sum total of these categories represents a 'total communications' score and the pattern of comms. can be characterized statistically with reference to a multiple regression based technique (Warm, Dember & Hancock, 1996). By this method, each individual category is analyzed in terms of its relative contribution to the aggregate 'total communication' score. Its contribution is expressed as a standardized beta coefficient, the higher the beta coefficient, the more that a comms. subscale contributes to total communications. This method provides an order of magnitude analysis highly useful for discerning patterns of communication such as this. Note also that an assessment of statistical significance is carried out on the beta-coefficients thus providing a means to assess the affect of random error and noise in the data (a statistically significant coefficient value is one that is unlikely to have arisen due to random error). The pattern of relative contributions made by each subscale varies across 'receive' and 'transmit' events as shown in Table 3.

Table 3. Standardized beta coefficients show the relative contribution that each voice comms. subscale makes towards total communications (for both transmit and receive events).

	Beta Coefficients		
	Receive	Transmit	Direction of Change
Factual	0.73*	0.33*	Down
Meta-Query	0.17**	0.67*	Up
Response	-0.30	0.67*	Up
Query	0.16***	0.67*	Up
Action	0.60*	0.67*	Up
Acknowledgement	0.40*	0.67*	Up
Judgement	0.43*	0.67*	Up

* Statistically significant at the 1% level
** Statistically significant at the 5% level
*** Statistically significant at the 10% level

What does Table 3 communicate about the pattern of voice comms.? First of all is the presence of a marked change in pattern between communications transmitted and received. Meta-Queries, Responses, Queries, Actions, Acknowledgements and Judgments make a uniform contribution to overall comms. in the transmit category, with Factual comms. assuming a lesser place. In other words, the output of BDE, in voice comms. terms, is less about 'objective statements involving verbalized readily observable realities of the environment' and rather more to do with 'requests to repeat or confirm previous communication, statements conveying more than one bit of information (i.e., comprising of more than simply 'yes/no'), direct or indirect task-related questions, statements requiring team members to perform a specific action, one bit statements following another statement (e.g., “yes,” “no”) and the sharing of information based on subjective interpretations of the situation.’ This pattern switches for comms. that are received. Here, the focus is very much on observable realities of the situation. The picture that emerges from this analysis is one of a ‘data’ vs. ‘information’ dichotomy, with the former associated with comms. received and the latter associated with comms. sent.

Table 4. Data vs. Information Received and Transmitted by Brigade Headquarters

	Digital %	Voice %
Level 1 (‘data’)	73	47
Levels 2 & 3 (‘information)	27	53

‘Data’ vs. ‘Information’ [sic]

Table 4 shows all comms. (digital and voice, both transmitted and received) divided into ‘data’ and ‘information’ meta-categories. As defined in the Methodology section above, data is taken to mean an emphasis on raw ‘elements in the environment’ (Level 1 SA according to Endsley’s model) whereas information emphasizes ‘comprehension and projection’ (Level 2 and 3 SA). Table 4 shows what the different comms. layers (digital and voice) predominantly carry in terms of this. From the table it is clear that the digital comms. layer carries a far higher proportion of data compared to the voice layer. This disparity is statistically significant ($x^2 = 14.08$; df = 1; $p < 0.0001$, and is accompanied by a moderate effect size; Cramer’s $V = 0.27$; $p < 0.0001$). Note that the Chi Square test has been performed on the percentage of the raw scores. The reason for this is that statistical power becomes excessively high with 3000 or so data points. Table 5 contributes further to this picture. It goes on to show that it is predominantly 'data' that is received by the BDE headquarters (96%) compared to a greater proportion of 'information' leaving it (26%).

Table 5. Data vs. Information Received and Transmitted by Brigade Headquarters

	Received by BDE	Transmitted by BDE
Level 1 ('data')	96	74
Levels 2 & 3 ('information)	4	26

This pattern of findings was once again subject to statistical tests to assess the probability that they did not arise due to random error. In this case $x^2 = 18.98$; df = 1; $p < 0.0001$ which means that there is a significant association between the direction of communications (transmit or receive) and their type (data or information). Or in other words, the observed results differ significantly and meaningfully from the results expected under the null hypothesis (e.g., Cramers V = 0.31; $p < 0.0001$, a medium effect size).

Overall, what these findings seem to indicate is that the incoming data arrives on the digital function as data and leave the BDE HQ on the voice function as 'information,' with the NCW system's interface sitting squarely in between. From the imbalance between data/information, the interface appears to act as something of a bottleneck. The alternative hypothesis (of Exploratory Hypothesis No. 2) is supported to some extent in that a possible design goal of future versions of the system might be to increase the proportion of 'information' on the digital layer from a lowly 27% to something more like the voice layer (approximately 50%). To express this in more vernacular terms, this is a lot of data (and a lot of bandwidth) for not much resultant information.

In wider social network terms it is interesting to note that the pattern of receive and transmit events resembles "a model of a biological organism" (Dekker, 2002, p. 95) in that "The organization receives [data] from its environment (intelligence), makes decisions, and produces some effect on its environment (force). [...] Ultimately, the performance of an organization (or an organism) depends on the appropriateness of its response to its environment" (p. 95).

Results: Structure of Communications

Digital Function

Center of Gravity

In order to perform a static characterization of the organization's center of gravity within the Approach Space, the space itself is divided into eight 'octants.' By this reckoning the social network metrics can indicate either broadness or tightness (in terms of decision rights), distribution or hierarchy (in terms of patterns of interaction), unitary or peer to peer (in terms of dissemination of information), or any combination thereof.

The 34 separate social network analyses performed on the digital comms. function produced 34 separate diameter, density and sociometric status figures. These were then divided into upper and lower 50th percentiles to create six categories pertaining to the octants described above (as shown in Table 6). The raw data was then transformed into category data (1 = Upper Percentile, 2 = Lower Percentile). The number of data points that fell into each category was then subject to a simple modal analysis to derive an 'average' network type. It will be noted that none of the categories are strongly biased in any particular direction, so this high level characterization is undeniably of a broad brush nature. The results of this analysis are shown in Table 6.

Table 6. Overall Characterisation of the Network Type Extant at the Digital Comms. Layer Compared to a Number of Social Network Archetypes

		Diameter	Density	Status
Digital Layer	Upper Percentile	16	17	18
	Lower Percentile	18	17	16
	Modal Point	Hierarchical	Broad/Tight (Tied)	Peer to Peer
Archetypes	Peer-to-Peer	Distributed	Broad	Peer to Peer
	Hierarchical	Distributed	Tight	Peer to Peer
	Circle	Hierarchical	Broad	Peer to Peer
	Chain	Hierarchical	Tight	Unitary
	Y	Hierarchical	Tight	Unitary
	Wheel	Distributed	Broad	Unitary

* Shading denotes closest match

The modal network derived from the above analysis was able to be compared against the earlier network archetypes, the Circle, the Chain, the 'Y' and the 'Wheel.' The results of this comparison are also shown in Table 6. It can be seen that the static characterization of the digital comms. function approximates most closely to the 'Circle' network archetype, which is to say that the center of gravity for this function is located in that vicinity. Bevelas and Leavitt's work highlights the performance advantages of this configuration under situations of high task complexity. In these situations the decentralized nature of the network helps to avoid bottlenecks and the overloading of just one, or of a few, heavily connected agents. So in terms of Exploratory Hypothesis No. 3 this is a match to where the organization desires to place itself (as a decentralized net-centric organization). Consistent with Exploratory Hypothesis No. 4, however, is the mapping between its location in the Approach Space and the corresponding location in the problem space, which reveals a mismatch (thus the alternative hypothesis No. 4 is supported). Plotting the archetypical networks directly into the NATO SAS-050 Approach Space as shown in Figure 6 locates the 'Circle' archetype in the bottom/right/back octant. The problem, i.e., the scenario which the live-NCW case study was charged with dealing, is an overtly cold-war style of engagement characterized by high familiarity (of enemy doctrine), fairly constant rates of change (to the extent that the dynamics are more or less linear and in sequence) and a high strength information position (a lot is known about enemy capability and position). The corresponding octant in the problem space is, therefore, in the region of the bottom/left/front octant. In this situation, the attributes of a circle network are less optimal than hierarchies, chain or Y networks. This is because the time taken to collate information begins to negate the benefits of decentralization. This precise phenomenon was clearly in evidence during the exercise and partly one of the reasons why users reverted to FreeText (as in hypothesis No. 1) in an attempt to speed things up.

Dynamic Characterization

If the structure of communications was stable then its center of gravity would be a sufficient characterization. Unfortunately, as the percentile data suggested (by not revealing a particularly strong category bias in Table 6) the network is far from stable, in fact it reconfigures dramatically in response to its environment. This reconfiguration is clearly evident when all 34 sequential social networks from the observed exercise are plotted into the Approach Space along with the archetypal networks. What results is a form of 3D scatter plot or 'phase space' that illustrates the dynamical behavior of the system over time. What is immediately clear, and perhaps contrary to the impression often given, is that the command and control organization is highly dynamic. The extent of the organization's agility can be seen in network density (i.e., distribution of information) varying about its mean of 0.84 by +/- 0.5. Similarly, the number of high status agents in the network (i.e., decision rights) varies from zero to four, and likewise, diameter (i.e., patterns of interaction) varies around 4.38 by +/- 3.5. These are pronounced changes in the structure of digital communications as illustrated by Figure 6.

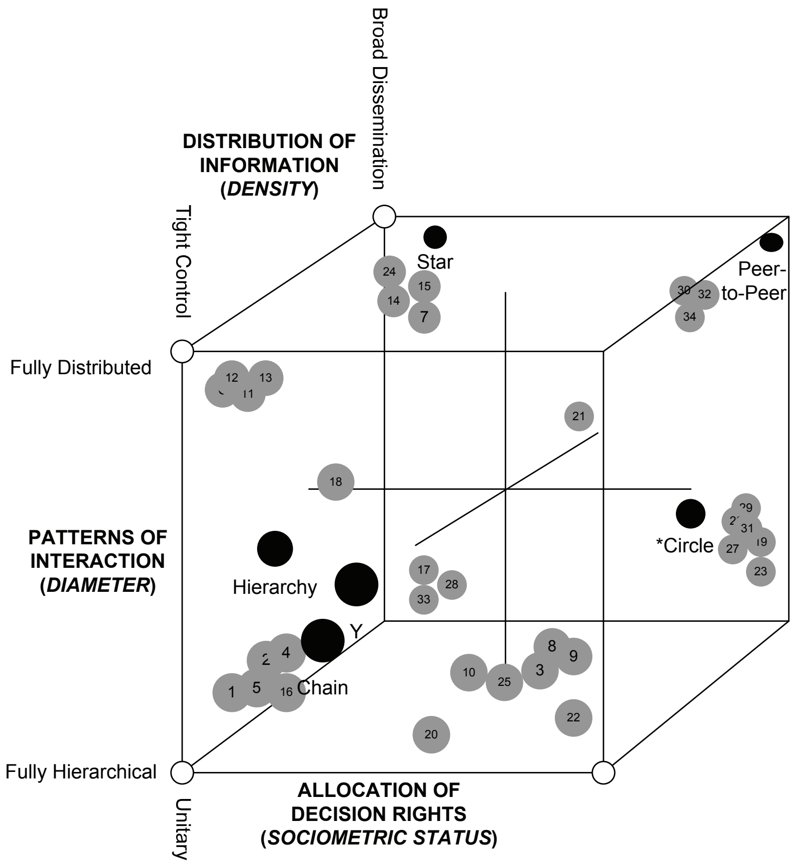

Figure 6. Illustration of the 34 separate social network analyses plotted into the NATO SAS-050 Approach Space to show how the configuration of digitally mediated comms. changes over time (grey numbered spots). The approximate position occupied by the network archetypes is also shown (black annotated spots). The 'modal' network configuration of the digital comms. layer approximated to a 'circle' archetype (marked with an asterisk).

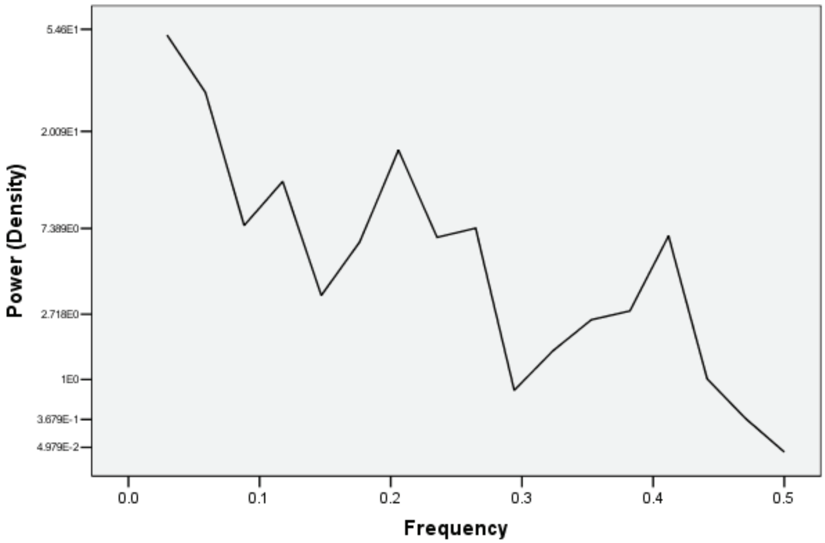

Figure 7. Periodogram illustrating the presence of periodic changes in network density. A pattern is obtained that approximates to first, second and third order harmonic effects.

Figure 7 is a periodogram of network density. This is the output of the spectral analysis method described earlier and is designed to detect the presence and strength of any periodicity in the data. The x-axis (marked frequency) represents a scale with very slow fluctuations in the distribution of information at the leftmost end, to rather more rapid fluctuations at the other. The pattern of results gained is intriguing. They show a power spectrum dominated by very low speed fluctuations in distribution of information accompanied by the presence of what appear to be second and third order harmonics of diminishing strength but increasing frequency. In other words, overlain on this slowly cycling level of network density is a higher frequency of network reconfiguration but at reduced power. Overlain on top of this is yet another higher speed reconfiguration. In the language of signal processing the time-series data seems to exhibit a fundamental frequency of reconfiguration (a strong periodicity) combined with second and third order harmonics at multiples of that fundamental. Distribution of information exhibits a strong, non-random and often rapid pattern of reconfiguration, with communications links able to establish (and re-establish) themselves repeatedly. This seems to indicate high tempo and, more fundamentally, an underlying theory governing the dynamical behavior which appears to be deterministic in character.

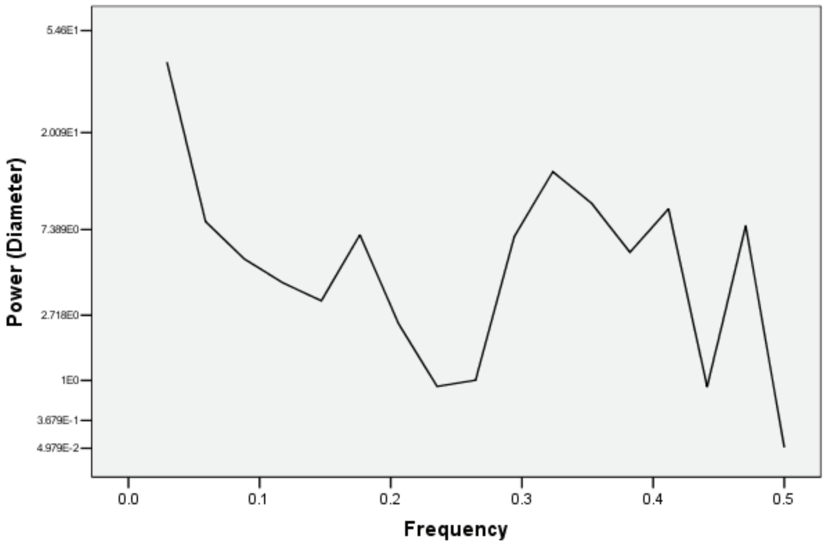

Figure 8. Spectral analysis graph illustrating the presence of periodic changes in network diameter.

Network diameter (i.e., patterns of interaction) also exhibits interesting behavior (Figure 8). Again, there is the presence of what appears to be a strong fundamental frequency (suggesting an underlying rate of expansion and contraction in the network's diameter) with something that could be taken for a second harmonic occurring at a multiple of the fundamental higher up the frequency range. What this graph communicates is that there are strong and non-random changes in the patterns of interaction, with comparatively rapid shifts occurring between fully hierarchical and fully distributed modes of operation. Again, high tempo seems in evidence.

The pattern of results observed above for network density and diameter is not similarly evident for sociometric status (i.e., allocation of decision rights). The power spectrum (not reproduced in this case) exhibits a more or less random pattern, a lower, more uniform power spectrum, and little evidence of systematic periodicity. In these terms, there is evidence that movement along the scale from unitary to peer-to-peer decision rights is rather low in tempo (relatively speaking) and governed by more non-deterministic factors that lack distinct patterns and fixed attractors in the phase/Approach Space.

Voice Function

Center of Gravity

The first stage of the analysis is to provide a static representation of the underlying voice comms. data by performing the same form of modal analysis as before. The results of this are shown below in Table 7.

Table 7. Overall Characterisation of the Network Type Extant at the Voice Comms. Layer Compared to Hierarchical and Peer-to-Peer Archetypes

		Diameter	Density	Status
Voice Layer	Upper Percentile	18	17	18
	Lower Percentile	16	17	16
	Modal Point	Hierarchical	Broad/Tight (Tied)	Peer to Peer
Archetypes	Peer-to-Peer	Distributed	Broad	Peer to Peer
	Hierarchical	Distributed	Tight	Peer to Peer
	Circle	Hierarchical	Broad	Peer to Peer
	Chain	Hierarchical	Tight	Unitary
	Y	Hierarchical	Tight	Unitary
	Wheel	Distributed	Broad	Unitary

* Shading denotes closest match

It can be seen that the static characterization of the voice function, like the digital function, approximates most closely to the ‘Circle’ archetype. The advantages of this configuration under situations of high task complexity have already been noted and apply here. But again, this appears to be a relatively poor match to the extant situation, perhaps even to a slightly greater extent than the digital function. In simple terms, for the scenario being faced by the organization it probably needs to be locating itself in the region of the hierarchy, chain and Y archetypes which in practice it does not, as shown in Figure 9.

Dynamic Characterization

The reconfiguration of the voice function over time is clearly evident when all 30 sequential social networks are plotted into the NATO SAS-050 Approach Space. Density (i.e., distribution of information) varies about its mean of 0.27 by +/- 0.9. Similarly, the number of high status agents in the network (i.e., allocation of decision rights) varies from zero to two, and likewise, diameter (i.e., patterns of interaction) varies around 1.06 by +/- 2. This seems to describe a similar extent of agility as the digital function, but is likely to be affected by network size (the digital function is larger). Further scrutiny is required to provide a more robust measure of this concept but the extended NATO SAS-050 now admits that possibility.

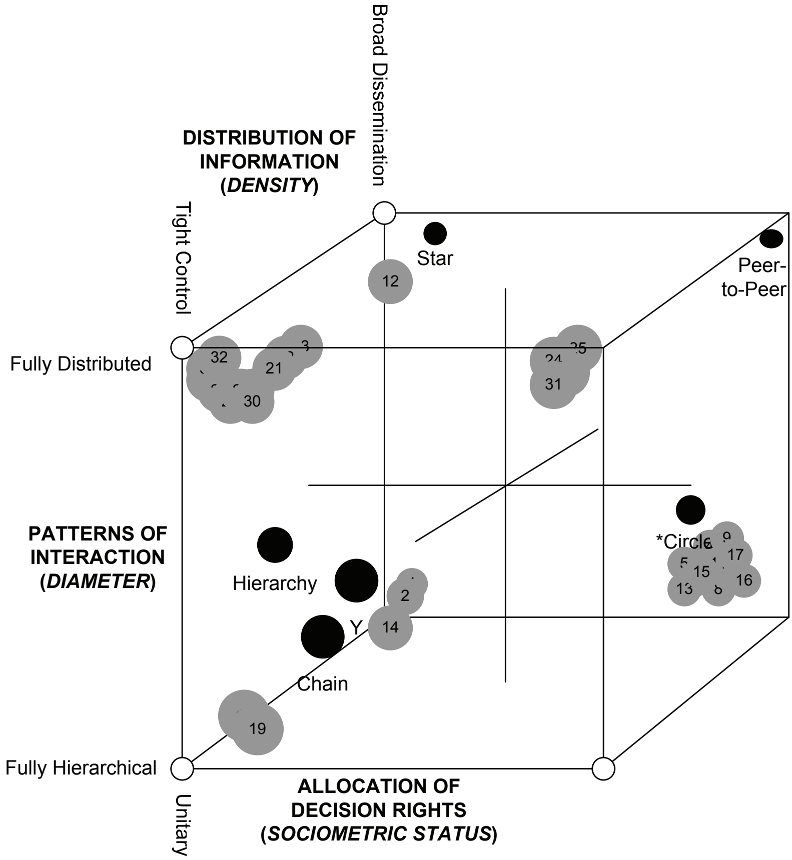

Figure 9. Illustration of the 34 separate social network analyses plotted into the NATO SAS-050 Approach Space to show how the configuration of voice mediated comms. changes over time (grey numbered spots). The approximate position occupied by the network archetypes is also shown (black annotated spots). The 'modal' network configuration of the voice comms. layer approximated to a 'circle' archetype (marked with an asterisk).

Reference to Figures 6 and 9 shows that the voice function appears more clustered overall, with the individual social networks tending to fall into more well defined areas of the 3D space compared to the digital function. One way to interpret this is to say that the voice function is characterized by powerful fixed attractors that control the dynamics of the function in more prescribed ways. Again, this could be due to the smaller size of the network. It is still interesting to note, however, that the Approach Space populated with the digital function lacks these fixed attractors and is characterized instead by strange attractors and more chaotic underlying dynamics. Spectral analysis may help to shed more light on this.

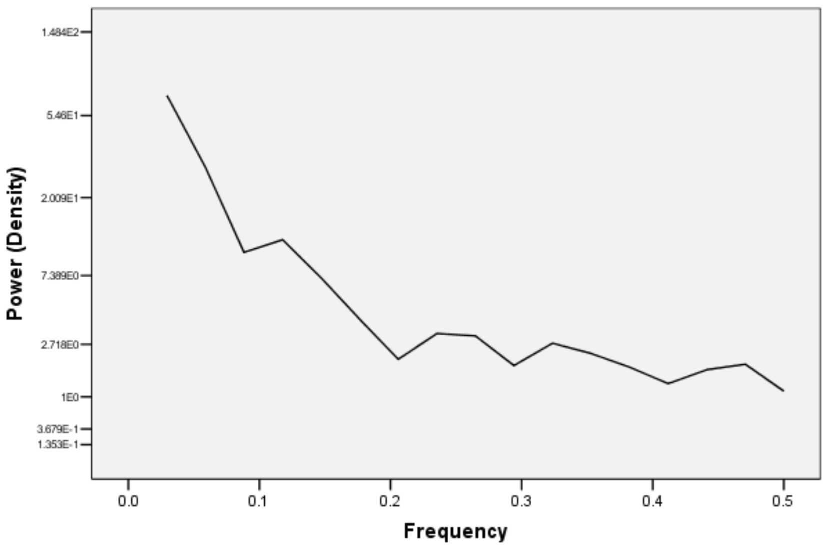

Figure 10. Spectral analysis graph illustrating the presence of periodic changes in network density. A more or less identical pattern of results is achieved for network diameter.

Figure 10 is a periodogram of network density (i.e., distribution of information) for the voice function. The pattern of results is more or less identical to those gained for network diameter (i.e., patterns of interaction) and given this similarity only the set of results for density/distribution of information need be reproduced. Figure 10 shows a power spectrum dominated by a very low speed fluctuation in network density and diameter, one that rather corroborates the more clustered appearance of the voice function Approach Space, which in this case is accompanied by slower tempo.

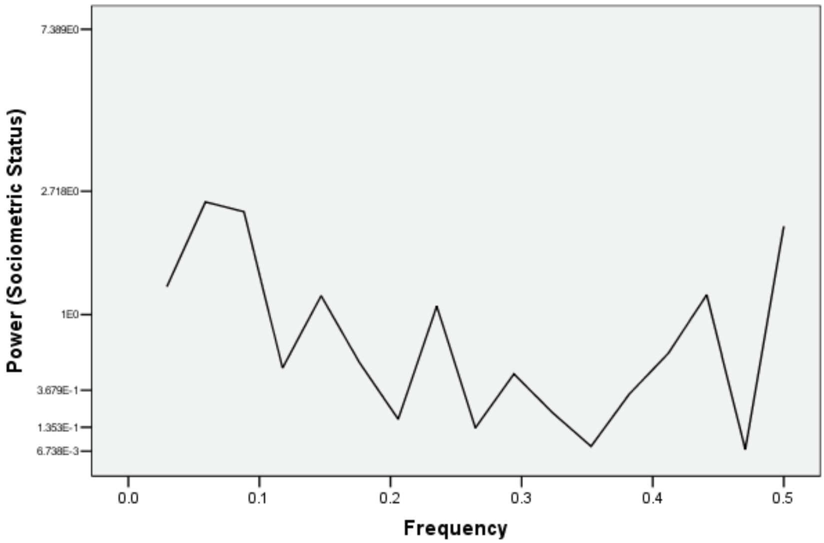

Figure 11. Spectral analysis graph illustrating the presence of periodic changes in high status nodes.

Unlike the digital comms. layer, the behavior of the network in terms of high status nodes (i.e., allocation of decision rights) is of an order of magnitude greater in terms of power (Figure 11). The pattern of results is difficult to determine but unlike the previous cases there are two discernible peaks in the spectrum that indicate a low and high speed change in decision rights. On this measure, the voice function appears to be governed by more deterministic forces that drive the resultant social networks into clusters rather than scattering them widely around the Approach Space as is the case for the digital function.

Conclusions

The key innovation presented in this paper is to use social network analysis in order to define quantitative metrics for each of the NATO SAS-050 Approach Space's primary axes. It is this simple expedient that has provided a practical means to define the actual place or region in the Approach Space where an organization operates, to see how that ranges over function (digital and voice) and time (by taking slices through the data). In addition, through the use of well understood network archetypes, a comparison between the approach and the problem to which it is directed has been facilitated. In summary, the use of both theoretical and live data demonstrates how the missing links of the NATO SAS-050 Approach Space can be filled.

The analysis based on this approach provides some interesting insight into the real-life challenges of introducing net-centric platforms in service. Emergent behaviors arose in which 'something stupid,' in this case a highly simplistic FreeText facility, 'bought something smart.' Whether this was an attempt by users to restore the mismatch between their net-centric approach and their corresponding cold-war style problem is debatable, but in either case it tells systems designers that users favored a 'simple system that enabled them to do complex things' rather than a 'complex system that only enabled them to do simple things.' Another interesting issue was that the presence of data, or even the network to carry it, was not enough on its own to increase operational effectiveness. The results of the present analysis hint that not enough of this is occurring in the present system and that greater attention toward the user/technology interface, and perhaps even the entire philosophy behind digitization, requires further evolution from a human-centric perspective.

A finding that goes to the heart of the NATO SAS-050 Approach Space is where the live organization actually positioned itself in practice. Its center of gravity clearly bore the hallmarks of a distinctly net-centric organization as defined by procedures and doctrine, but it was the users, in attempting to meet the challenges created by their 'problem,' that pulled this organization into virtually all areas of the Approach Space. By and large it was down to them and their interpretation of the system, the way they massaged it and made such adjustments as they saw fit, that gave the system its resultant levels of agility and tempo. The fact that the system, in the end, was able to provide such a level of agility and tempo is very encouraging but as mentioned above, there was a fundamental mismatch between approach (i.e., NEC) and problem (i.e., cold war) which seemed very hard to overcome. Indeed, success in the mission required arduous efforts on the part of those involved and to some extent occurred despite the presence of net-enabling technology rather than because of it.

There is still much work to do on what is admittedly a relatively fresh innovation. Future work is directed at taking this data, which concerns the 'what' of this particular live-NCW scenario, and discerning the 'why.' In particular, examining the scenario in much more detail and mapping it across to the social networks that arose. Additional future work is being pursued in the following areas: refining the model metrics, exploring how they behave at different scales, how they can be normalized in order to populate the NATO Approach Space with historical data from organizational science, how concepts from complex systems research can be spun-in, and how a similar quantification of the 'problem' space can be performed. These and other issues are all being vigorously pursued. For the time being, in the same vein as the NATO SAS-050 Approach Space, this work too is offered as a point of departure for researchers, analysts, and experimenters engaging in C2-related research.

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