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Some Non-Technical Limitations on NEC/NCO Concepts

Michael K. Lauren (Defence Technology Agency, New Zealand Defence Force, NZL)

Abstract

This article discusses the limitations of Network Enabled Capability from the point of view of the dynamical properties of conflicts and the physical constraints of networks, rather than technological limitations. The discussion focuses principally on the observed power-law nature of conflict (that is to say, treating warfare as a hierarchy of conflicts within conflicts). It is suggested that the resulting broad range of scales for which military action can occur may not lend itself well to a ubiquitous computer interface and network. Furthermore, any overarching computer network may face significant challenges in connecting to the furthest reaches of the C2 chain, due to the physical limitations in maintaining connectivity. The conclusions of this article suggest that a good strategy for addressing these limitations may be to place emphasis on connections necessary for specialist, high-payoff applications which benefit the most from close collaboration, with only intermittent connections for other applications.

Background

New Zealand has recently articulated its need to move to a new paradigm of managing and controlling its forces, to keep up with modern Command and Control (C2) practice. In its concept document the New Zealand Defence Force (NZDF) describes a capability which enables intense collaboration between its military units, coalition partners, and non-military agencies. Like the United Kingdom, it describes this as Network Enabled Capability (NEC) (see UK MoD JSP777 and NZDF Supplement to JSP 777). However, in such documents there is often an absence of quantitative description of what the limitations are in implementing the capability. This lack of quantitative understanding can lead decision makers to aspire to *Star Trek*-like technologies.

In this article, the intention is to examine what – beyond the simple state of the technology – limitations might be found. This is done by utilizing the emerging understanding of warfare, both conventional and insurgent, as a complex system displaying power-law properties.

There is now a growing literature on the existence of power laws in conflict data. The existence of these power laws implies the presence of self-organizing processes, so that it would be wrong to view command chains as strictly flowing from the top to the bottom. Rather, ad hoc connections emerge between commanders and elements in response to events, and these may involve cross-organization or bottom-up processes. Since these power laws appear to exist in historical data, it is reasonable to assume that such self-organization occurs regardless of C2 technology.

There have been a number of theories which attempt to improve the understanding of warfare dynamics by incorporating these ideas. An example is the research conducted at NZ's Defence Technology Agency (DTA) and associated collaborations under the auspices of The Technical Cooperation Panel's (TTCP) Joint Systems and Analysis Group's Technical Panel 3 (Lauren et al. 2007).

Some earlier versions of these ideas were presented in the CCRP publication *Complexity Theory and Network Centric Warfare* (Moffat 2003).

Existing Concerns over the Network Enabled Capability (NEC) Concept

NEC is effectively the UK Ministry of Defence's response to the US's Network Centric Operations. This deviation from the American terminology reduces the emphasis on networks, while still developing a compatible concept. In practice, the main difference between NCO and NEC is likely to be in the practicalities of implementation, with each nation selecting solutions that are appropriate to its budget.

Both NEC and NCO are long-term change programs. More than likely, NEC and similar concepts are an inevitable reflection of continuing technological change, and indeed it may be impractical to maintain many of the old analogue technologies still in use by some nations.

While the perfection of the use of communications technology to achieve combined arms effects has long been a goal of systems engineers, NEC is seen as a distinct concept where the existence of the network itself is believed to be a force multiplier. More specifically, it is supposed to create a knowledge edge that enables a force to act faster and more decisively than its opponent (Cebrowski 1999, Alberts et al. 2000).

If such a knowledge edge is a force multiplier, then it may allow a shift from reliance on weight of armor and firepower, meaning that the next generation of forces may be lighter and more agile, and therefore more easily deployable (Alberts and Hayes 2005). Taken at face value, such ideas could be seen as trading armor for information while maintaining a similar level of combat effectiveness, though to say so is an oversimplification of the concept, as clearly a NEC force could comprise of any mix of elements.

Nonetheless, arguments that information can be traded for armor make for an interesting analogy with British Admiral Lord Fisher's concept that "speed is armor" in the design of Dreadnought-era battle cruisers. An advantage in speed has the tactical benefit of allowing a ship to choose not to engage a superior opponent. Additionally, their greater mobility made these ships more suitable for deployment to protect the distant shipping lanes of the Empire. They were not intended, however, to stand and fight against the more heavily armored battleships. Rather, they were designed for situations where they held the upper hand in an asymmetric fight.

While the concept enjoyed some overwhelming success in the early part of the First World War, it also endured some disasters when battle cruisers were used in more conventional "line of battle" roles. The only modern capital ships lost at the Battle of Jutland were battle cruisers.[1] A similar situation occurred in the Second World War when the old battle cruiser Hood was disastrously pitted against the modern battleship Bismarck. Suffice to say, it would not be without precedent for forces to be deployed into roles for which they were not ideally suited, and this needs to be kept in mind in considering such trade-offs.

Though the historical cases above are not directly analogous, it is reasonable to question how much emphasis should be put on the potential to lighten force mixes as a result of utilizing NEC/NCO concepts. A systematic "lightening" in the mix of a nation's military

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[1] Since the loss of three of the four battle cruisers sunk has been attributed to poor cordite handling, it is difficult to know how critical the armor deficiencies were, though certainly their protection bore some of the blame at the time. The point here, though, is that while nearly invincible in one role, the limitations of their armor made them much more vulnerable when facing guns of similar calibre to their own. The concept therefore never supplanted the premier role of the battleship as the major capital ship type, as perhaps Adm Fisher might have thought possible, and battle cruisers remained a specialist unit built in small numbers. Ironically, the greater speed of these ships caused them to be used in a manner which put them at the forefront of the clash at Jutland.

capabilities is especially seductive given that the cost of implementing such networks may have to be met by sacrifices in other areas, such as protection, and that the deployment and sustainment costs of light forces is lower.

Indeed, many criticisms of NCO center on concerns that the concept is encouraging an overreliance on networks to improve the ability of units to succeed in what is essentially a brutal task. For example, Kaufman (2004) claims that NCO concepts have led to what he believes is a grave oversimplification of how future wars will be fought and the importance of computer networks to them. He also claims that these concepts have been accepted by much of the military establishment in the US without the rigorous systems analysis that had been standard prior to its emergence.

On the other hand, there certainly is evidence that NCO improves combat effectiveness. Findings by the US Government Accountability Office (GAO) (2004) point to increased lethality of US forces due to NCO capabilities, principally in the task of matching shooters to sensors and assessment of subsequent missions by integrated C2 centers (e.g. in bombing missions). Moreover, the NCO concept is continuing to evolve to address such criticism.

It might be reasonable to assume, then, that NEC/NCO is of benefit, and provided that the budgets can be found, politicians and the senior leadership can be relied upon to provide a suitable balance of force type, network-centric tactics and practical warfighting.

In this article, therefore, the focus is not on the validity of the NEC concept, but rather on its fundamental limitations. The author hopes that the work presented may contribute to progress in understanding where the bounds are in terms of what is feasible for NEC/NCO, and therefore aid planners in avoiding development dead-ends.

Dynamics of Military Operations

The approach used to analyze warfare dynamics in this article is most easily understood in the context of an operational theatre based on land, and in essence is an evolution of the classic industrial-age mathematical model of warfare, the Lanchester equations (1916). These simple, aggregated equations of warfare are governed by the number and relative strength of each side in a military confrontation. Consequently, they are often considered an industrial age paradigm, where industrial might determines the victor.

They represented a potent paradigm shift at the time of their introduction, and these equations were still being used towards the end of the 20th Century to estimate force size requirements in a potential confrontation with Soviet-pact forces in Eastern Europe. Largely, however, their relevance has waned as the nature of operations has changed.

Moreover, numerous studies have demonstrated that, in fact, the original form of these equations is not consistent with the historical outcomes of battles (e.g. Helmbold 1995, Perry 2006). Most likely the reason for this is the failure to take into account the tactics used and Command and Control.

Work under the auspices of TTCP's JSA TP3 and already presented within the CCRP forum (Moffat et al. 2004) offers an alternative, updated view of the Lanchester approach, using the principles of self-organizing systems to suggest that warfare should be viewed as a process which generates large-scale patterns as a result of small-scale interactions between the parts of a conflict.

One type of such pattern is a power-law. A distinguishing feature of systems that display power laws is that there is no characteristic scale or frequency of event. Therefore, in the military context, casualty events can be of any size but become less common the larger they are. This is a property that casualties from insurgent attacks, for example, have in common with other power-law systems, such as earthquakes. The existence of power laws in warfare data is very well established, both for conventional and insurgent wars (for example, Richardson 1941, Roberts and Turcotte 1998, Lauren and Stephen 2002, Dobias and Sprague 2009, Bohorquez et al. 2009).

One interpretation of this empirical fact is that casualty distributions can be understood in terms of a "Fractal Attrition Equation" (Lauren 1999, Lauren and Stephen 2002, Lauren et al. 2007, McIntosh and Lauren 2007). This equation was originally proposed by analogy to the famous Kolmogorov expression for describing the structure function of velocity increments in high Reynolds Number turbulence (Lauren 1999), although there are other suggested means for deriving this expression (Lauren et al. 2005). In terms of the statistical structure function for the increments in combatant numbers (i.e. the casualty rate), the proposed equation has the form:

$$\left\langle \left| N(t+\Delta t) - N(t) \right|^2 \right\rangle \propto O_{cluster}{}^2 k^D \Delta t^D \qquad (1)$$

where N is the number of remaining units belonging to the force upon which the fire is directed, O_{cluster} is the number of units in a typical opposition cluster that generates the fire, k is a measure of the effectiveness of the weapons being employed by the firing units, Δt is an arbitrary time interval, D can be interpreted as a fractal dimension, and the angled brackets denote an ensemble average over different times t. Importantly, when the power D is a non-integer in this equation, the distribution of casualties can be regarded as being fractal-like, at least for some range of scales.

The most common description of a fractal is as an object which exhibits structure on all scales. Thus, Eq. (1) implies that casualty data ought to also display such scaling properties, so that there appear to be "battles within battles" when the distribution of casualties is fractal.

Much like the Lanchester equation, this Fractal Attrition Equation is most usefully employed as a pedagogic tool, intended to improve understanding rather than to be used in any real predictive sense. Nonetheless, it has been shown that Eq. (1) can be used to theoretically explain the disparity between historical battle outcomes and traditional Lanchester models (Perry 2006), from which it can be concluded that D is indeed a non-integer for historical battles.

Note that although we have used combatant attrition in the example above, the expression might be applied to model other distributed effects, such as food distribution rates in a humanitarian operation.

In essence, this equation says that the rate of attrition for a conflict is determined by the distribution of the forces on each side, as described by D, as well as the number of units and their firepower. C2 quality is reflected in Eq. (1) by assuming that the force with superior C2 will have the advantage in the way it is able to deploy itself in the battlespace.

The fractal-like scaling properties of warfare are often played on in wargaming, where aggregated units may be used to represent groups of soldiers and equipment without bothering to deal with the behavior of individuals within the group. Events for a battle represented at a level of aggregation for which battalions are the smallest unit may look similar to a much smaller battle with a similar number of platoon-sized units—the key difference being the duration of the battle. If time is slowed down or sped up by an appropriate scaling factor, it becomes impossible to determine which battle is which. This time scaling follows from the relationship between the spatial size of the battle and the rate of movement of various units across the battlespace.

It can be argued that generally commanders in the field do the same thing, i.e. view the battlefield as consisting of the aggregated units which are most relevant to their rank. Doing so means that each level of command deals with a similar level of information, uncertainty, number of options, and computational complexity, and in this sense each scale is self similar: i.e. the dynamics are such that to a degree each scale evolves independently of each other, but all levels of command are looking at similar kinds of maneuver schemes once the labels and scales are removed.

What does change with rank is the level of aggregation that is necessary to be used in order for this self similarity to become apparent (that is, senior commanders need to use a greater level of aggregation in order to reduce their picture of the battlefield down to a similar number of degrees of freedom as a junior commander). Also, the rate of evolution of the system at that level of aggregation changes. Senior commanders have more time to think about how to arrange the units under their command, but it also takes longer to gather information—since there is more information that needs to be aggregated—to accurately represent the situation at this level.

When not using aggregation in this manner, the commander, instead of seeing the battlefield as a hierarchy of nested military problems, sees it as growing rapidly in terms of information and computational complexity as his rank increases. Focusing on smaller scale actions may occasionally be necessary if a senior commander needs to delve into details to solve a particular problem, but doing so in the course of conducting an operation risks exposing himself to information overload and excessive cognitive burden, as well as potentially failing to observe how the system is evolving at a higher level of aggregation.

Another thing that changes at different rank levels is the way that uncertainties are handled. For a large unit it takes longer to collect the information to be aggregated, so there is greater scope for its commander to choose the level of uncertainty that can be tolerated in decision-making. Conversely, the commander of a small unit may be conducting actions which occur at sufficient tempo that there is little time to either gather further information or consider decisions at length. Furthermore, the commander in that situation will likely already know most of the relevant information, since it is right there in front of him.

Thus a senior commander has more responsibility given the ability to influence multiple levels of command, but more time to choose when to take actions and under what level of uncertainty. A junior commander has a simpler problem in terms of options, but decisiveness and rapid action are much more important.

There are two important points in this. First, latency in communication is a more critical issue for small units than for large, since the timescales involved in completing actions are shorter, i.e.:

$$\text{Appropriate decision latency} \propto \text{Rank and corresponding Area of Operations} \quad (2)$$

Thus what commanders might describe as real-time information might more appropriately be thought of as relevant-time information. Clearly, though, this is not a hard and fast rule, rather a reflection of what the dynamics tend to.

Secondly, and likewise, it can be argued from the above that micromanagement of small units by officers commanding larger units tends to run against the natural dynamics of conflict. This does not mean that micromanagement cannot or should not occur, rather that the action of attempting to micromanage an operation must work in opposition to the natural dynamics of conflicts, as well as the memory and processing limitations of the human brain.

Empirically Observed Properties of Casualty Data

Eq. (1) implies that the Fourier Transform of a casualty time series ought to display a power law of the form:

$$C(f) \sim |f|^{-\beta} \quad (3)$$

where C is the number of casualties that occur in some event, f is the frequency of that level of casualties occurring, and β is related to the fractal dimension D. This expression describes how casualty events become less frequent the larger the number of casualties that occur within them.

Detailed analysis of Second World War casualty data has verified this, providing some degree of validation for the Fractal Attrition Equation (Lauren and Stephen 2002), though the relationship between β and D remains to be conclusively proven.

Importantly, the same work also established that, as with turbulence, the distribution of casualties in a time series exhibits temporal clustering. In particular, casualty distributions appear to fit a multiscaling fractal distribution of the form:

$$\left\langle \left| C(\Delta t) \right|^{q} \right\rangle \propto \left(\frac{\Delta t}{T} \right)^{-K(q)} \qquad (4)$$

where C is the number of casualties in a time interval Δt, T is the duration of the entire time series, and K is a non-linear function of the q^{th} statistical moment.

More recent work by Dobias and Sprague (2009) and Sprague et al. (2011) has demonstrated the intermittent nature of casualty data from contemporary operations in Iraq and Afghanistan, using related techniques.

What the works above show is that the variance in casualty data increases as a power-law as the resolution of the data becomes finer. Thus, as one views the battlespace at increasingly fine resolution, the action appears more concentrated within particular time intervals (and, it follows, locations).

A further implication is that, since activities are increasingly clustered in time and space as the resolution (and hence the size of the unit in question) is reduced, at any given time a given subunit can generate a disproportionately large amount of activity, i.e. it may conduct a much larger share of the action than would be expected if the conflict were uniformly spread across the battlespace.

We can observe this phenomenon more directly by examining historical combat data. Figure 1 shows the number of TOW expenditures from the Bradley armored fighting vehicles of Eagle Troop of the 2nd Armored Cavalry Regiment at the Battle of 73 Easting, during Operation Desert Storm, 26 February 1991. It is apparent that there was considerable variation in the amount of firing that occurred from vehicle to vehicle (Bolmarcich 2003). This kind of pattern has been shown to exist in the historical data from other conflicts (for example, number of aircraft killed by carriers in the Vietnam War) by the same author.

This observation is suggestive of another scaling law: (5)

$$\text{Maximum required bandwidth by unit} \propto (\text{size of unit})^{P}, P < 1$$

which is to say, the maximum potential bandwidth requirement to capture all action from a unit operating in a discreet area during some fixed time interval does not fall in proportion to the unit's size, i.e. small units may on occasion generate a disproportionately large requirement for C2 services for the size that they are (but more often than not, do not need this level).

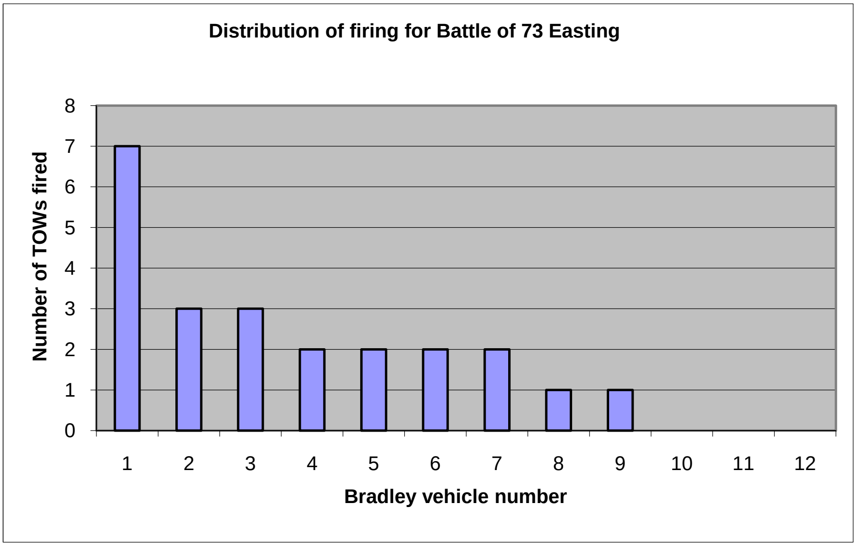

Figure 1. Number of TOW firings per Bradley Armored Fighting Vehicle for the Battle of 73 Easting, 1991

In fact, Eq. (5) more or less follows from Eq. (4), if one views casualties as a type of information, which may be done by imagining the information requirements to describe in detail the casualty incidents, and by noting the relationship between time and space on the battlespace. Because casualties are clustered in the battlespace according to a power law arrangement, then so to is at least some of the associated information.

Larger units also require a large amount of bandwidth due to their size, but are using it more continuously.

Interpreting Scaling Laws in Terms of Impact on a Command Network

The scaling arguments presented above are particularly important to computerized C2 systems because of the way that their interfaces tend to be designed. Generally speaking, it is necessary to represent information at some preferred level of aggregation to prevent information overload and direct the user's attention to the most useful information (Sanderson 2005).

This is because human beings are known to be only capable of recalling four or five items immediately after they are presented with visual information, and this recall rate drops very quickly after a few seconds (Marois and Ivanoff 2005). As a consequence of these operator limitations, careful consideration needs to be given to the dissemination, design and display of information.

However, addressing this issue is difficult, because according to Eq. (2), different levels of command work on differing timescales, so that what is appropriate to one level may have inherent and intolerable levels of latency to another. This equation is suggestive, therefore, of a need for specialized interfaces, some dealing with less-detailed information and greater latency, but allowing a greater appreciation of the broader picture; and some providing greater detail and lower latency, but suffering from a narrow focus.

This problem is more complicated than a simple question of how to present information. Challenges result from inherent uncertainties and partial information in dealing with real operational environments (Franconeri and Simons 2003, Cianciolo 2003). Moreover, it is reasonable to assume that each level of command has associated with it its own uncertainties. Even if an interface can allow a commander to "dig down" into information, it may be unduly onerous to the front-end users to have to maintain information on the network that is sufficient for all levels of command, as well as explaining the associated uncertainties.

We have already noted that the dynamics of warfare may at times not lend themselves well to micromanagement by senior officers. At least some experiments seem to confirm this, as human factors testing carried out at the University of Melbourne (Wearing 2007) indicates that an increased degree of input from a high-level commander into lower-level commanders' duties tends to decrease overall performance, even when the higher commander has the impression that the operation is improved (these types of impressions are usually attributed to the commander's increased sense of control). There is also anecdotal evidence of the perils of this, such as the tale of Operation Anaconda by Sean Naylor (2005).

The dynamics suggested in the previous section also present problems in terms of connectivity of command networks. According to Eq. (2) latency is most critical at the fringes of the organization (i.e. small units conducting tactical tasks). Such units also require mobility, and therefore a wireless connection to the C2 network. However, there are significant technical issues which arise with wireless networks in terms of their ability to provide adequate throughput (Porche and Wilson 2006). For example, experimental results suggest that per-node throughput for wireless networks decays like (Gupta and Kumar 2000, Gupta et al. 2001):

$$\sim n^{-1.68} \qquad (6)$$

where n is the number of nodes.

Why this is a concern is that—as shown in the previous section—bandwidth requirements become increasingly concentrated in time and space the finer the resolution with which demand is viewed. Therefore one might expect periods where local demand for wireless network connections spikes very significantly above the mean, particularly during critical actions such as combat. In short, the properties of wireless communications nodes seem to work in opposition to the dynamics of conflict.

Kopp (2007) further identifies 15 constraints on high-capacity mobile networks, the most critical of which are the physical size requirements necessary for radio transmitters and antennae, limitations of wireless signal propagation, availability of radio spectrum, and network congestion constraints. Kopp argues that these hard physical constraints mean that bandwidth cannot grow limitlessly for mobile, ad-hoc military wireless networks.

Indeed, there is evidence from the Iraq War that some front-line ground units were poorly served with information, at least partly due to connectivity difficulties (Talbot 2004).

When the observations on the nature of conflict dynamics described in the preceding section are combined with these human performance and physical network connectivity limitations, it suggests that there exists fundamental limits to what may be achieved with NEC/NCO technologies, which are not simply a function of the current state of the technology. This is important, because it is not always clear to decision makers that such limits exist, or that perhaps these cannot be simply solved by some assumed future technology.

It should be acknowledged, however, that many of the technical issues (versus dynamical limitations) cited above could ultimately be tractable, at least in the sense that there may be workarounds. For example, airborne or satellite relays, for which transmitter size and propagation are not so restricted, may be more effective at providing bandwidth to heavily engaged units lying relatively isolated from a ground network point of view. The affordability of such solutions, though, may be an issue for some nations.

Whatever the technology, efforts to bring real-time high-bandwidth global operating information to the fringes of the military organization via a ubiquitous computer interface, as expressed in some operational concept documents, seem unlikely to ever be completely successful. Furthermore, such a network is only as useful as the quality of the information on it. Even ignoring potential connection issues in relaying information to the network, the units at the fringes may find it difficult to constantly provide high-fidelity real-time updates.

Rather, it may be sufficient to allocate whatever bandwidth is available at the fringe to specialist, high-payoff applications. This raises the question of what level of global network access should be provided to other units at the fringe beyond the existing mechanisms for implementing C2 (such as transmission of voice commands and other information over a small and localized network)?

It may be more beneficial to focus on powerful tools which do not require high bandwidth or low latency, such as e-mail, social networking tools, Wikipedia, and Google Maps-like applications. It would be difficult to argue that such tools have not had a significant impact in the information age, and therefore should be seen as having great potential as warfighting tools. Indeed, examples of the use of such capabilities already exist, for example, by US Special Forces hunting for Taliban elements in the mountains on the Afghanistan-Pakistan border (Talbot 2004).

For these applications, individuals collaborate to add content, but the information is provided "as is" by individuals with the time and inclination to do so. Because they do not necessarily require much bandwidth, central hierarchy, or need to operate in real-time, they would not necessarily be constrained by the mechanisms described in the preceding sections. Moveover, these technologies are enablers of self-organization. It would therefore be reasonable to say that this is the sort of Information Age technology that could be feasible, affordable, and beneficial to add at the fringe of the military organization.

Summary

Within this article, a developing formalism has been outlined in which conflicts may be viewed as having dynamics in which battles occur within battles, and for which no “special” scale exists. There is now a growing literature that shows that such scale-free patterns exist, both for conventional and insurgent conflicts.

It is argued that, in viewing conflict as such a system, different levels of command must often work on incompatible timescales. Conversely, computerized representations tend to focus on a preferred scale to prevent information overload and draw the user’s attention to the most useful information, forcing the users to focus on a single scale. This sort of incongruity between technology and the dynamics of warfare is suggestive of the existence of fundamental limitations on what NEC/NCO systems can add to military capability, which go beyond the simple question of the current technological state of the art.

For example, issues such as the degree of uncertainty in information presented in any given SitRep are likely to be hidden from commanders not on the spot, and limitations such as this may not have a feasible solution.

It also follows from the mathematical arguments presented that demand on communication nodes may be prone to spike at the fringes of the command network. Unfortunately the properties of some kinds of wireless networks work in opposition to such dynamics, as throughput slows dramatically as more nodes attempt access.

The combination of these phenomena suggests that difficulties in the implementation of NEC/NCO reported by some sources should come as no surprise, and are likely more than just teething issues. This does not mean that NEC/NCO cannot be a successful concept, rather that there may be a need for greater awareness of its limits, hand-in-hand with appropriate targeting of development.

A likely strategy for successful implementation of digital-age C2 for smaller countries, at least, is to place emphasis on connections necessary for specialist, peer-to-peer high-payoff applications which benefit the most from close collaboration, while accepting that low-bandwidth applications with intermittent connections would likely be the most practical solutions to generating an additional information advantage.

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