17th ICCRTS

"Operationalizing C2 Agility"

Megatrends Reshaping C2 and their Implications for Science and Technology Priorities

Topics:
(1): Concepts, Theory and Policy
(2): Approaches and Organizations

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Abstract

This paper identifies four interrelated megatrends that individually and collectively are shaping not only the state of the art and practice of C2, but also the mission challenges we face. These megatrends are: (1) The wide availability of advanced commercial information and communications technologies; (2) The increasing complexity of endeavors as military establishments form coalitions and partnerships; (3) The rise of decentralized, net-enabled approaches to C2; and, (4) The data deluge. These megatrends lead to a set of C2 challenges that can, in part, be addressed by Science and Technology (S&T). We identify six C2-related S&T areas that we believe deserve urgent attention because they are on the critical path to operationalizing C2 Agility.

Introduction

Command and Control (C2) technology sits at the nexus of most of the major developments in information and communications technology of the past two decades. It involves information processing, sharing, collaboration, networking, multimedia, and wired, wireless, and satellite communications. As part of the broader universe of Command, Control, Computers, Communications, Intelligence, Surveillance, and Reconnaissance (C4ISR), it also involves imaging technologies.

The state of the art and practice of C2, the nature of the missions we undertake, and the environment in which these missions are undertaken are being continuously shaped by the following four interacting "megatrends", depicted in Figure 1:

> (1). The extremely broad availability of advanced information and communications technologies that place unprecedented powers of information creation, processing, and distribution in the hands of almost anyone who wants them—friend and foe alike;
>
> (2). The increasing complexity of endeavors as military establishments form coalitions with each other, and partnerships with various civilian agencies and non-governmental organizations;
>
> (3). The rising importance of decentralized, net-enabled approaches to C2; and,
>
> (4). The data deluge—the unprecedented volumes of raw and processed information with which human actors and C4ISR systems must contend.

These trends interact with each other in various ways. The complexity of endeavors demands complex enterprises, which often operate more effectively in a decentralized, net-enabled manner. Decentralized complex enterprises often generate larger volumes of information than hierarchical ones, contributing to the data deluge. Meanwhile, advanced commercial information and communications technology enables and facilitates both complex endeavors and net-enabled decentralized approaches. It also empowers more actors to create more information, and thus contributes directly to the data deluge.

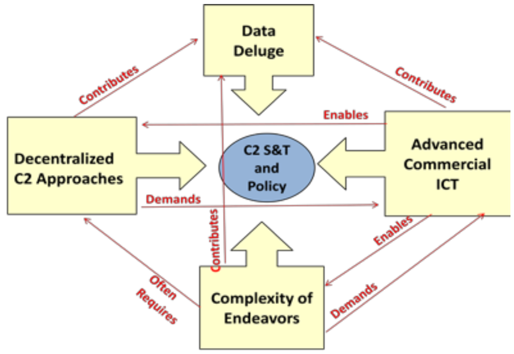

Figure 1. The future of C2 science and technology, as well as C2 policy, is being shaped by at least four interlocking major trends.

We begin below by discussing the megatrends in more detail, and analyzing their C2-related implications. This leads to a set of critical challenges for C2, some of which can be addressed by developing a better understanding of the nature and behavior of new, net-enabled approaches to C2 and their relationship to improved C2 Agility. We conclude the paper by identifying a number of important C2-related S&T topics that require our attention if we are to achieve the objective of this Symposium, that is, to Operationalize C2 Agility.

<u>The Four Megatrends Shaping C2</u>

<u>*Megatrend 1: Advanced Commercial Information and Communications Technologies*</u>

The rapid progress of advanced commercial information and communications technologies (ICT) has placed unprecedented computing power, information storage, information processing, and connectivity into the hands of almost anyone who wants it. Such technologies include personal computers and peripherals, networking, geolocation, and mobile telephony. It is important to note that while many of these technologies have military origins, much of the tremendous progress in ICT in the last two decades has been in the commercial arena, posing both a set of opportunities and a set of challenges. Not too long ago, military-developed technologies often drove commercial applications. This relationship has, in some cases, been reversed in recent years as commercial ICT developments and products now offer unprecedented opportunities for increasing the effectiveness and efficiency of military operations. On the other hand, these same opportunities are available to others, posing a significant challenge.

When one lives in an era of rapid progress, the changes can appear almost commonplace, and it is easy to take them for granted and forget their profundity. It is thus helpful to review some basic statistics. One useful case to consider is mobile telephony. Perhaps no other technology represents so many facets of the revolution in ICT: computing power, multimedia, storage, and connectivity, with both hardware and software aspects being crucial. In 2001, there were 15.5 mobile cellular subscriptions for every one hundred people in the world. In 2010 there were 78. The growth was particularly striking in the developing world,[1,2] which went from only 7.9 cellular subscriptions per 100 people in 2001 to 70.1 in 2010.[3] Meanwhile, the developed world had, by 2010, more cellular subscriptions than people (114.2 per 100 people, compared to 47.1 in 2001).[4] In 2003, 61% of the world's population resided in an area with cellular coverage. By 2010 the figure was 90%.[5] This all represents a truly staggering growth in communications power and connectivity for individuals and organizations everywhere.

Not only has mobile telephony exploded in numbers of handsets and subscriptions, but the character of the handsets and the range of available services have also radically improved. "Smartphones," that is, handsets capable of accessing the Internet, producing and receiving imagery and video, and a myriad other functions, have gone from being elite items a few short years ago to becoming the dominant handset in some areas. In the U.S., the proportion of cellular phones that were smartphones was only about 10% in 2008.[6] By the third quarter of 2011, smartphone penetration in the U.S. was 49%,[7] and 65% of all new handsets being shipped in the U.S. were smartphones.[8] Globally, the figures were lower, but still significant: nearly 30% of new phones shipped worldwide towards the end of 2011 were smartphones,[9] and mobile broadband subscriptions stood at 12.6 per 100 people.[10]

To put the power of smartphones in perspective, compare them to computers of the past. The LINPACK[11] benchmarks for numerical computation test the speed of a computer for a particular set of matrix calculations.[12] While LINPACK results are by no means a measure of total system performance, they are a useful indicator of one important dimension of computing power, and they also have the advantage that they have been recorded for decades. A Cray 1 supercomputer—the fastest computer in the world in 1979—had a performance of about 3.4 MFlops.[13,14] A Cray XM-P-4 supercomputer from 1986 had a performance of about 220 MFlops per processor.[15] Some of the most recently benchmarked smartphones exceeded the latter number, with the fastest one being over 258 Mflops![16,17]

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1 Definitions of "Developed" and "Developing" world are those used by the United Nations; see UN (2012).

2 OECD (2011)

3 ITU (2011, 2012)

4 ITU (2011, 2012)

5 ITU (2012)

6 Kwoh (2011)

7 Kwoh (2011)

8 Vision Mobile (2011)

9 Vision Mobile (2011)

10 ITU (2012)

11 LINear equations software PACKage

12 Dongarra et al. (1979); Dongarra et al. (2001); Dongarra (2007, 2011)

13 A "MFlop" is one million floating-point operations per second.

14 Dongarra (2007)

15 Dongarra (2007)

16 Greene Computing (2012)

As for bandwidth, the current "fourth-generation" or "4G" cellular technology, as exemplified by the LTE (Long-Term Evolution) specification, is capable of average data rates of 8-20 Mbps[18], depending on the particular implementation.[19] The previous generation of service, "3G" (as exemplified by the ITU's[20] IMT-2000 specification[21]) was capable of average data rates of 1-2 Mbps before the various enhancements that eventually led to 4G.[22] The ITU's vision for 4G is 100 Mbps in high-mobility applications, and 1 Gbps[23] in low-mobility ones.[24] It is interesting to compare these numbers to the data-rate performance of some military radios (although one should proceed with caution in making such a direct comparison, given additional military requirements for security, resistance to jamming, etc.). For example, the U.S. military still uses some SINCGARS radios, first introduced in 1988.[25] Even after improvements, these radios are only capable of data speeds up to 16 kbps.[26] The Soldier Radio Waveform of the Joint Tactical Radio System (JTRS) is supposed to be able to achieve 1 Mbps.[27] JTRS's Wideband Networking Waveform (WNW) may achieve up to 5 Mbps.[28]

Other indicators of the explosion in commercial ICT are not difficult to find. Costs of hard-drive data storage have dropped from around US$700 per Gigabyte in 1995 to as low as 7 US cents per Gigabyte in 2009.[29] In 2001, only 8% of the world's people used the Internet. By 2010 the figure was 29.7% (nearly 68.8% in the developed world, and 21.1% in the developing world).[30] The global Internet has gone from moving an aggregate of about 1 Exabyte[31] of data per month in 2004 to 21 Exabytes of data per month in 2010.[32] The social networking site Facebook, virtually unknown outside

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[17] To the best of our knowledge, these benchmark figures for various devices are roughly comparable. However, one must still exercise caution, since there are a number of different LINPACK benchmarks, corresponding to different matrix sizes, and not all investigators always quote which one they are applying. Also, some investigators report observed performance while others calculate theoretical peak performance over one computational cycle, and not all investigators specify which number they are quoting.

[18] Mbps = million bits per second if using the decimal scale

[19] Plumb (2012)

[20] ITU = International Telecommunications Union

[21] IMT = International Mobile Telephony; see ITU(2003)

[22] ITU (2003)

[23] Gbps = billion bits per second if using the decimal scale

[24] ITU (2008)

[25] Kagan (1999)

[26] JITC (2012)

[27] JITC (2012)

[28] JITC (2012)

[29] Komorowski (2011)

[30] ITU (2012)

[31] An Exabyte is 10^{18} bytes, or a billion Gigabytes, if using the decimal scale. If using the binary scale, an Exabyte is 2^{60} bytes, or about 1.153 x 10^{18} bytes. Unfortunately, most sources do not specify which definition they are following. General-interest literature usually uses the decimal scale.

[32] Miller (2010); Cisco (2012)

Harvard University at the beginning of 2004, had almost 800 million users by the end of 2011—around 11.5% of the world's population.[33]

These developments have significance beyond simply presenting an opportunity for the U.S. Military to enhance its capabilities. This is not a "take it or leave it" opportunity. Rather it is imperative to seize it, because *the computing and connectivity technologies essential to C2 systems are available to almost anyone*, friends and foes alike. Non-state actors and governments alike can take advantage of them. Under some circumstances, such adversaries may be able to use the afforded capabilities to outmaneuver a large, modern military that uses legacy ICT.

Another important point is that the young people who are joining the U.S. armed forces are completely immersed in advanced commercial ICT; to this "Net Generation," legacy C2 systems and their associated technologies may seem ineffective, and perhaps almost quaint. For these young people, creating, processing, transmitting, and sharing large amounts of multimedia information are matters of routine.

Megatrend 2: Complex Endeavors

In the past few decades, the mission space associated with military operations has expanded to include a broad spectrum of challenges[34,35]. In some cases, allied nations may create complex coalitions to pursue an objective[36]. If the coalition becomes involved in peacekeeping and nation building, it may need to collaborate with military and civilian entities in the host country, as well as non-governmental organizations and private ones. In other cases, for example disaster relief operations, military organizations may collaborate with a relatively large number of governmental and non-governmental entities[37]. These are all examples of complex endeavors. Advanced, widely available commercial ICT serves to increase the number of potential actors.

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[33] IW (2012)

[34] From an almost exclusive focus on traditional combat operations, the DoD has expanded the scope of its missions to include stabilization, reconstruction, peace keeping and humanitarian disaster relief. See for example, USDoD (2005).

[35] In addition to Stability, Security, Transition, and Reconstruction (SSTR), the military has been involved in Security for "Special Events". For example the DoD was involved in security-related planning for the 1996 Centennial Olympic Games in Atlanta along with more than a dozen other Federal, State, and Local government entities. See Howitt and Leonard (2009).

[36] Multinational efforts are now commonplace. These include current U.S. efforts in Afghanistan and Iraq

[37] Hurricane Katrina, which struck Louisiana on 29 August 2005, required a multi-dimensional response involving hundreds of entities. Moynihan (2009) noted that "The Katrina network was so large that there was a failure to fully comprehend all of the actors actually involved (partly because of a large voluntary component), the skills they offered, and how to use these capacities [House Report 2006: 302]. One study counted over 500 different organisations involved in the weeks after landfall [Comfort, unpublished data]." See Moynihan (2009).

In complex endeavors, there may be multiple interdependent chains of command, and the intents and priorities of the various participants may not be perfectly aligned[38]. The collaborating entities may also have differing perceptions of the same situation. This complexity can make it difficult to make timely decisions, develop appropriate plans, and take necessary actions.[39,40]

Experiments show that the complexity of endeavors can have the effect of forcing more decentralized approaches to C2. Approaches to collective C2 can be characterized according to the degree of information dissemination among the entities, the degree to which interaction patterns between the entities are constrained, and the breadth of allocation of decision rights.[41] This is depicted in Figure 2. As one moves through the center of the conceptual cube, from the lower left vertex to the upper right, the C2 approach becomes more decentralized and net-enabled. The Edge approach is the most decentralized.

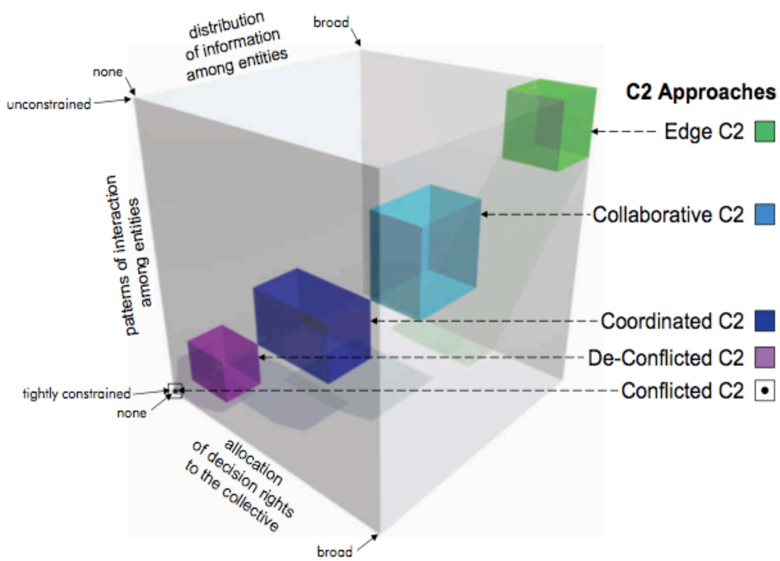


Figure 2 (From Alberts et al., 2010). Varyingly decentralized approaches to C2 in complex endeavors involving a number of cooperating entities. "Edge C2" is the most decentralized.

Figure 3 shows the results of experiments[42] conducted using the U.S. Department of Defense's abELICIT[43] experimental environment. We will not dwell on the experimental

[38] In the response to the Indian Ocean Tsunami of 26 December 2004, there were militaries from 11 countries involved. Each had a somewhat different relationship with the Indonesian Government. A case study undertaken in support of NATO SAS-065 noted examples of a lack of shared intent. See Huber et al. (2008), p. 15.

[39] Alberts et al. (2010)

[40] During relief efforts associated with the Indian Ocean Tsunami, a Humanitarian Information center was established in an effort to provide some oversight for hundreds of NGOs. Their daily meetings were characterized as being “unwieldy” and as “ a shambles” See Huber et al. (2008), p. 4

[41] Alberts and Hayes (2006); Alberts et al. (2010)

[42] Experiments conducted in preparation for Alberts (2011)

details; the experiments were not conducted specifically for this paper but in preparation of the book *The Agility Advantage*.[44] Here, we are mainly interested in the results. In the experiments, agents were presented with a set of mission challenges that varied by: 1) the nature of the mission; 2) mission requirements; 3) the difficulty of the problem (its cognitive complexity); 4) the level of noise in the available information; and, 5) the state of the communications and social network. The "task" in these experiments was to correctly identify the parameters of an attack (who, what, when, and where). The major experimental treatment was the C2 Approach that was adopted. Success was determined by whether or not the required[45] level of effectiveness,[46] (a combination of timeliness and shared awareness) was achieved. In addition to effectiveness, a measure of efficiency[47] was also calculated at the end of each run. C2 Approaches were compared, one to another, by looking at their relative agility,[48] that is, their ability to be successful over a range of challenges.

Examining Figure 3, one can see that a major finding from the experiments is that complex endeavors (such as those involving coalitions) appear to require more decentralized and net-enabled C2 approaches. Hierarchical C2 approaches could only effectively prosecute simple endeavors. Edge C2 approaches (the most decentralized and net-enabled) could handle complex ones.

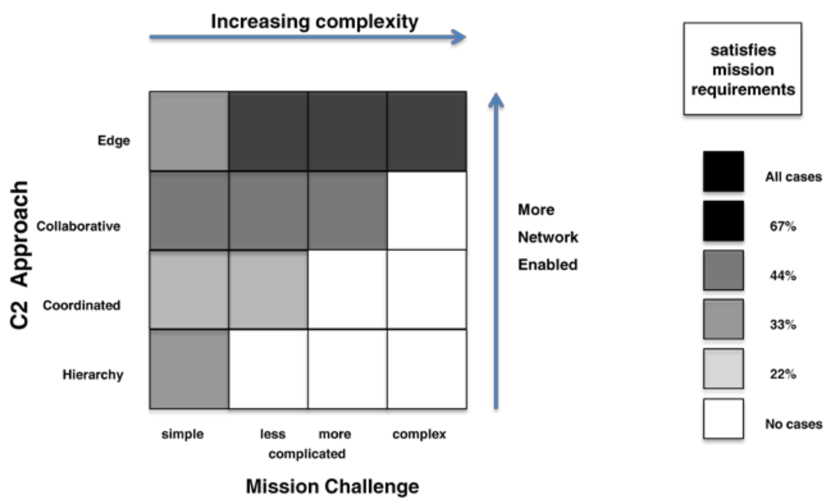


Figure 3. Results of experiments conducted in preparation for Alberts (2011). Complex endeavors tend to require a more net-enabled and decentralized approach to C2.

[43] CCRP(2010); ELICIT stands for Experimental Laboratory for the Investigation of Collaboration, Information Sharing, and Trust; abELICIT is the agent based version.

[44] Alberts (2011)

[45] The specified minimum level of shared awareness and timeliness

[46] Measures of effectiveness were (1) Timeliness (the time to the first correct solution) and (2) shared awareness (the average correctness).

[47] The measure of efficiency was (average correctness)/(number of transactions)

[48] Percentage of the Endeavor Space (a multi-dimension space that represents the various characteristics of the mission) where the C2 approach satisfied mission requirements.

Megatrend 3: Decentralized, Net-Enabled Approaches to C2

Complex Endeavors (Megatrend 2) require Complex Enterprises. Complex Enterprises are increasingly recognizing that they must adopt, where appropriate, more net-enabled, decentralized approaches to accomplishing the functions associated with C2 (Megatrend 3). This third megatrend is also being driven by the recognition that dynamic, uncertain environments cannot always be sufficiently understood and controlled using industrial-age hierarchical approaches. This recognition is reflected in various high-level strategic plans in the United States Department of Defense.[49] It also is embodied in the Mission Command doctrines of the United States and other allies of the North Atlantic Treaty Organization (NATO).[50]

Consider the United States Marines in Afghanistan. In 2009, a marine regiment[51] might patrol a very large battlespace, possibly tens of thousands of square miles in size. Such a large area might formerly have been assigned to a whole division of several regiments. The 2nd Battalion, 7th Marines (2/7) alone conducted operations over 10,000 square miles in Afghanistan.[52] A battalion[53] was once the smallest Marine unit that would engage in independent operations; more recently, a company[54] or even a platoon[55] may do this. The large responsibility and the dispersed nature of the adversary have resulted in a considerable amount of autonomy for small Marine units. They largely follow[56] a relatively decentralized mission command[57] doctrine. This recalls General Charles Krulak's concept of a "strategic corporal in a three-block war."[58]

Another driver of Megatrend 3 is Megatrend 1, which has enabled a number of adversaries to adopt decentralized organizations, approaches, and operations. To the extent that these approaches make adversaries more agile, an effective counter requires increased agility on our part. Net-enabled, decentralized or edge approaches have been found to be more agile. Thus, Megatrend 1 is not simply an enabler of Megatrend 3; there can be a direct cause-effect relationship between the two.

The approach space depicted in Figure 2 referred to the ways a set of independent (yet inter-dependent) entities could work together, for example, members of a coalition. However, a similar approach space can be constructed for individual entities--for example, each member of a coalition, or any independent organization. Figure 4 shows such an approach space, along with notional positions of various military organizations

49 USDoD (2008, 2009)

50 e.g., USArmy (2003); USMC (1996); Canada DND (1996); UKRAAF (2008); see Vassiliou (2010).

51 Around 4,000-5,000 marines, but this can vary

52 Price and McHuen (2009)

53 Notionally about 300-500 marines, but can be more. The 2/7 has about 800 troops.

54 Notionally about 110 marines

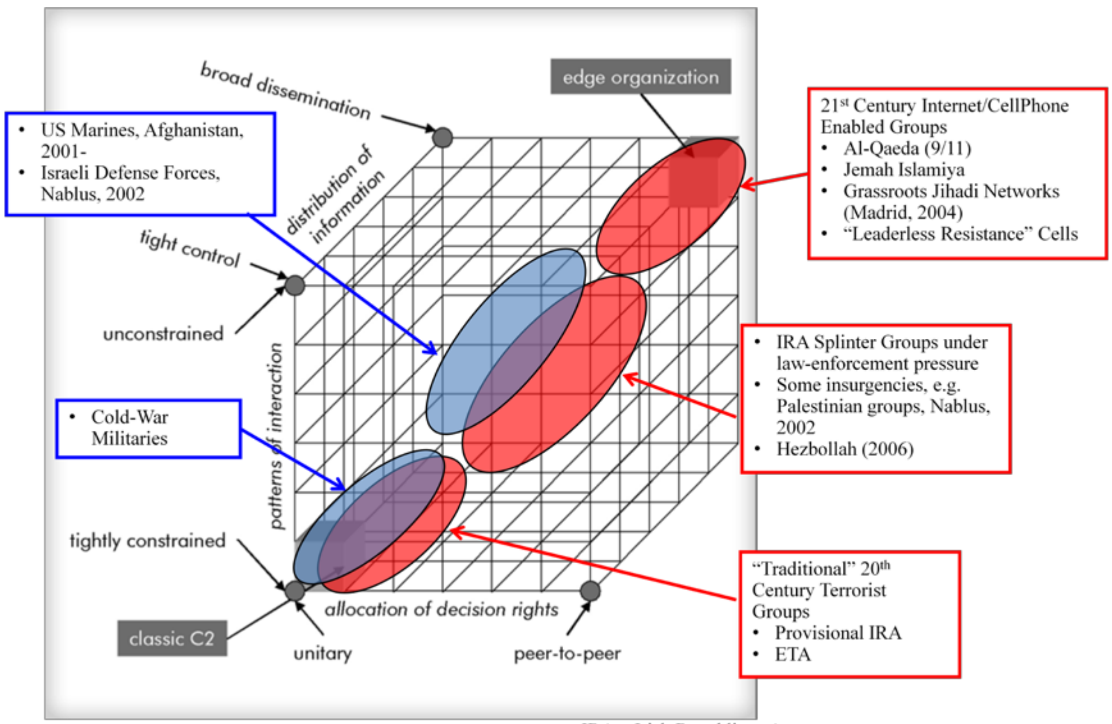
55 Notionally about 36 marines

56 Conversation with a U.S. Marine major

57 USMC (1996)

58 Krulak (1999)

and non-state actors. Vassiliou (2010) discusses examples in detail. Several terrorist groups, such as Al-Qaeda in the run-up to the attacks of 11 September 2001, display highly decentralized "edge" C2 behavior. The Israeli Defense Forces (IDF) behaved in a partially decentralized manner in Nablus in 2002 against a partially decentralized adversary. They behaved in a more traditional, centralized manner against a partially decentralized Hezbollah in 2006, with less success.



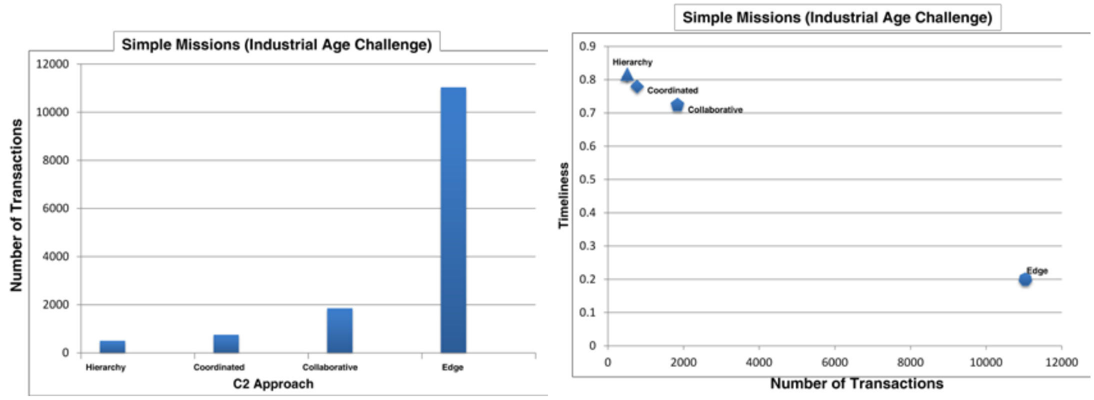
IRA = Irish Republican Army
ETA = *Euskadi Ta Askatasuna* (a Basque separatist group)

Figure 4. (from Vassiliou, 2010, and Alberts and Hayes, 2006). The approach space for various individual organizations.

While net-enabled, decentralized approaches to C2 can handle complex mission challenges better than industrial-age hierarchical C2, this capability comes at a price. With more quasi-autonomous actors each potentially creating information, the total available information naturally increases. Since more net-enabled approaches (e.g., collaborative and edge) share information more widely and interact more with one another, the number and flows of information will increase non-linearly. The result is a data deluge that, if not adequately handled, will result in information overload. This can degrade an entity's or a collective's effectiveness, even when they are faced with relatively simple challenges. Figure 5 shows the results of some abELICIT experiments[59] with simple, decomposable industrial-age missions. Figure 5(a) shows that, with more quasi-autonomous actors creating and demanding information, the decentralized, more net-enabled "Edge" approach to C2 creates far more information transactions than more centralized, less net-enabled approaches. Figure 5(b) shows that the resulting information overload can cause the Edge approach to generate solutions less

[59] Conducted in preparation for Alberts (2011)

quickly than the more centralized approaches. However, the less centralized approaches achieve higher levels of shared awareness.



(a) (b)

Figure 5. Results of abELICIT experiments[60] on C2 approaches to simple, industrial-age missions. (a) Number of transactions vs. C2 Approach (b) Timeliness vs. Number of Transactions.

Megatrend 4: The Data Deluge

During a conference on C2 held at the Institute for Defense Analyses in 2011,[61] an officer from the United States Marine Corps recounted an illustrative anecdote. He had participated in the 2003 march to Baghdad. For about three weeks during that time, he was disconnected from his email. On arriving in Baghdad, he found over 1,600 messages waiting for him. He remembers being angered, for two reasons: first, that he could have used some of those messages; second, that, even if he had received all his messages in a timely fashion, he might not have been able to separate the useful from the useless, particularly under the stress of a combat advance.

The Marine officer's dilemma has become commonplace in both the military and civilian worlds. Megatrend 4, the Data Deluge, is a direct result of Megatrends 1 and 3. As a result of Megatrend 1, anyone can create and disseminate information on a scale that heretofore would not have been possible, let alone economically viable. The cheaper and more widespread the technology, the worse the problem potentially becomes. Advanced and cheap commercial technology, as discussed above, empowers adversaries to create more information and disinformation that must be sorted and analyzed. The technologies eventually make their way into the military and their coalition partners in some form, and serve to increase both the coalition's information exchanges and each participant's internal flows and transactions, with the potential for information overload. The problem created by Megatrend 1 is exacerbated by Megatrend 2 (Complex Endeavors) and Megatrend 3 (the decentralization of C2), as we discussed above. In some situations, every soldier is a potential source of information in the form of text, image, and video that could be critical to the mission, and that must be processed, viewed and digested.

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[60] Alberts (2011)

[61] IDA/OASD(R&E) Conference on Commercial Technologies in C2, held at the Institute for Defense Analyses, Alexandria, Virginia, on 10 May 2011. Proceedings are in an IDA internal document.

In the wider universe of C4ISR, data sources continue to multiply. Persistent aerial video surveillance over city-scale areas requires imagers of the order of Gigapixel size, leading to raw, uncompressed data rates in the hundreds of Megabits per second and beyond.[62] Apart from the bandwidth and storage-related challenges posed by such massive quantities of information, there is also the currently unmet challenge of who will view all the footage and analyze it. Speaking of one such imaging system, an engineer from a major aerospace contractor said: "You can have 180 people looking at one [...] feed."[63] Recent research has also suggested that a human analyst eventually reaches a physical threshold for how much information he or she can process at one time, ultimately determined by blood flow to the brain.[64]

<u>Implications of the Four Megatrends for C2 S&T Priorities</u>

Each of these megatrends has important implications for the nature of the C2-related S&T that a country interested in effective C2 must undertake, if it is to remain successful both as an organization and as part of a larger coalition. Below we highlight six inter-related S&T topics that we believe need to be addressed with the greatest urgency. The inter-relationships that exist between and among these topics makes the progress we can achieve in improving both the state of the art and the state of the practice of C2 dependent on progress in all of these research areas, and also on our ability to translate our improved understanding and advances in theory into fielded capability. Therefore, we recommend that plans for this research be developed in an integrated fashion and that efforts to pursue these lines of research proceed collaboratively and with shared awareness. Note that the topics below are *not* presented in order of priority.

<u>*Priority Topic: New, Net-Enabled Approaches to C2*</u>

The four megatrends we have identified, taken collectively, pose an existential threat to C2 as we know it. The inaugural issue of the International C2 Journal[65] was devoted to papers on "The Future of C2". It opened with an article that began with the statement that the "future of command and control is not Command and Control."[66] That is, the future of command and control will lie in new paradigms and not in traditional, hierarchical industrial-age C2 systems. This conclusion was essentially based upon considerations similar to our Megatrends 2 and 3, the rise of Complex Endeavors and the creation of net-enabled, decentralized approaches to accomplishing the "focus and

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[62] To arrive at this rough figure, consider the problem of surveilling an area of 25 square kilometers with 15cm resolution, a bit depth of 20 bits per pixel, and a frame rate of 15 Hz.

[63] DTI (2012)

[64] Parasuraman and Wilson (2008); Parasuraman (2011)

[65] The International C2 Journal may be found on the CCRP website at www.dodccrp.org The link to the inaugural issue is http://www.dodccrp.org/html4/journal_v1n1.html

[66] Alberts (2007)

convergence functions of command and control without a reliance on a unified chain of command or an integrated set of systems supporting decision making and planning."[67]

Virtually all of the work that has been done on the science of organizations has been predicated upon the same set of assumptions that underpin traditional command and control organization and processes. Even when the nature of "self" changes from consisting of forces and resources that belong to a single entity to those that belong to a collection of sovereign entities, each with its own leadership, values, objectives, constraints, and cultures, the search for a C2 approach to "managing" the collection of entities begins and ends with an effort to create and impose a super-organization and work out lines of authority and decompositions of responsibilities. This approach to collective "organization" persists, despite the infeasibility of accomplishing it in practice.

Instead of pursuing this unproductive effort to push a square peg (a collective) into a round hole (a super hierarchy), we need to conceptualize, develop and explore other "forms" of organization with the rigor of science. Put another way, the approach space (Figure 2) needs to move from the realm of metaphor to theory and experimentation and then to practice and assessment. This will involve fundamental work in the topology and behavior of interconnected and interdependent sociotechnical networks. It will also involve new approaches to organization theory, and contributions from sociology, economics, psychology and other social sciences.

Moving from some form of hierarchy, even hierarchies that involve significant collaborative behaviors, involves moving along the dimension of the approach space that considers the allocation of decision rights. In fact, while pictured in the approach space as a single dimension, the allocation of decision rights is itself multi-dimensional. Research is needed to explore the ways in which the allocation of decision rights can differ. For example, in Hierarchies the "allocator" of decision rights is fixed and known while in edge organizations the allocation of decision rights is dynamic and emergent. Another difference that needs to be explored is how decision rights are expressed. Military organizations recognize expressions of decision rights in forms that range from "mission command" to detailed "orders". In order to identify potentially useful regions in the approach space for complex enterprises, the approach space itself needs to be developed further to understand fully all its dimensions. It must then be operationalized.

New net-enabled approaches to C2 not only apply to collectives, but also apply to entities with a single or, at least, an integrated chain of command, such as the U.S. Military, or various other government agencies. There are large regions of the approach space that remain unrecognized and heretofore unexplored.

Priority Topic: The Information Conundrum

Our second C2 S&T priority involves addressing what we call the C2 Information Conundrum. This is the clash between the demands of Complex Endeavors (Megatrend

[67] Alberts (2007)

2) for more decentralized edge-like approaches to C2 (Megatrend 3), and the behaviors found in Complex Enterprises that actually *adopt* such edge-like approaches. Complex mission challenges require cross-stovepipe access to information in multiple dimensions. Edge-like approaches seek to enable self-synchronization and collaboration by sharing information broadly to develop shared situational awareness. However, the information sharing and collaborative behaviors associated with Edge organizations greatly increases the number and size of information flows and the number of interactions between and among participants (all intensified by Megatrend 1, the broad availability of cheap and advanced ICT). This makes taming the Data Deluge (Megatrend 4) far more challenging than in Hierarchies and other organizational forms that place restrictions on access to information and constrain interactions by mandating pre-specified processes.

S&T is urgently needed to understand how we can fine-tune net-enabled approaches to shape their behaviors so that enough information is found, processed, and shared to satisfy mission requirements, *and no more*. One possible approach to this might be to explore forms of self-regulating information sharing and collaborative behaviors that are informed by shared awareness of the state of the Enterprise, to include an awareness of the state and performance of the communications networks, information flows, and the state of task progress.

To complement this organization and process-related S&T, there is a need to find and develop methods and tools to reduce the adverse impacts that information-related workload can have on entity effectiveness and timeliness. These include better software tools for sorting needed information from "noise" and automated assistants to perform information posting and sharing tasks.

<u>Priority Topic: Agile C2</u>

Complex Endeavors and Enterprises pose new dynamic, uncertain, and risky sets of challenges. The appropriate response to this is not to exacerbate the data deluge by focusing exclusively on more and more collection, processing, and analyses; but rather to learn to live with these new realities by becoming more agile.[68]

As we have discussed above, the decentralized edge-like approaches to C2 demanded by complex endeavors also have drawbacks. There is no "one size fits all" C2 solution. The most appropriate approach depends on the mission and the circumstances. Agile C2 is the capability to understand what C2 approach is appropriate and adopt it as a function of the dynamics of the situation. C2 agility is thus about moving around in the approach space in response to changes in endeavor space. The theory of C2 agility has been broadly sketched, but the subject is by no means well explored or understood. S&T is needed to test extant theory and conceptual models and to systematically explore the enablers and the inhibitors of agility.[69] This will involve extensive instrumentation of real-world situations in order to observe C2 behaviors. It will also entail further

[68] See Alberts (2011) for why this is the case

[69] Responsiveness, versatility, flexibility, resilience, adaptiveness, and innovation

experiments in C2 approaches using human participants. Finally, it will require development of integrated simulation environments that span the entire "Observe-Orient-Decide-Act" (OODA)[70] loop.

Priority Topic: Trust

There is one attribute of a person, organization, system, or information source that can make or break an entity—either enabling success or guaranteeing failure. This is *trust*. A lack of trust can freeze information in place, while appropriate trust assessments can move the right information along to the right places.

In light of Megatrend 1, which has made ICT capability ubiquitous and thus, placed this capability in the hands of adversaries, extra vigilance is warranted. The importance of placing appropriate trust in the information we access and the individuals we share it with cannot be overemphasized in light of the on-going efforts to deny, degrade, compromise, or corrupt this asset.

New, fundamental research is required to elucidate how individuals and groups form trust assessments, and how they act in light of these assessments. Understanding these dimensions of trust will help us determine how to make appropriate evaluations of trust, and how to act accordingly in C2 systems. Learning the consequences of given levels of trust on the information sharing dynamics of networked entities will help us select the most effective approach to C2 based on trust levels. It is also important to develop an understanding of how trust is built, and if that process can be accelerated in distributed environments. Similarly, it is important to understand how trust can be degraded, in order to protect against such degradation, or to visit degradation upon an adversary.

The ability to make appropriate trust assessments depends, in part, upon what we know about the information in question. Additional research is needed in the general field of data quality and data quality metrics.[71] As an example, we need to find ways to improve the "tagging" of data to provide potential users with more information about its collection or production as well as its provenance. Enabling C2 systems to explicitly (and in the future, automatically) take the quality dimensions of the underlying data into account will reduce uncertainty in the decision space and hence enhance decision-making capability.

Priority Topic: Taming the Data Deluge

All the priority topics above address aspects of Megatrend 4, the Data Deluge. For example, we have discussed the need for fine-tuning net-enabled C2 approaches so that only enough information is found, processed, and shared to satisfy mission requirements, and no more. A greater understanding of trust in networks may also help narrow choices and prioritize the handling of large quantities of information. However, there are also other relevant areas of research that are more directly related to the filtering and

[70] Observe, Orient, Decide, Act (OODA) is a paradigm developed by John Boyd, extensively used in the C2 community. See Boyd (1995).
[71] Agre et al. (2011); Strong et al. (1997)

processing of large volumes of data. A specific and important part of this problem is the processing and analysis of large video streams. More research is needed in the area of on-board processing close to the sensor. What processing is needed? What features should be retained, and what should be discarded? How much should be saved, given the limitations of transmission bandwidth and on-board storage? How much should be analyzed immediately, and how much should be archived? Given the limitations in the number and quality of human analysts, more research is needed in automated pre-analysis, particularly in automated incremental change detection. Additional work is also needed in optimal video compression algorithms. The highly successful commercial standards, such as those of the MPEG family and ITU H.264, are ideal for scenes in typical movies and television shows, but are not necessarily optimized for the requirements of image registration and intelligence exploitation.

Priority Topic: Embracing Commercial ICT

Advanced commercial ICT is a fact, and the technologies are available to friend and foe alike. It has thus become imperative that the U.S. military embrace commercial technology and make full use of its potential. This is not to say that the U.S. military establishment can or should replace all its ICT with commercially available products from the open market. The military may have unique requirements, particularly regarding security. In this connection, though, it is worth noting that there has been a certain convergence of needs between the commercial and military spheres even in the security area, and some commercial products can be highly secure. The Blackberry smartphone, for example, is secure enough that it could not be monitored by the presumably very capable intelligence services of the Kingdom of Saudi Arabia.[72] Still, military requirements for ruggedness, security, and low probability of exploitation may often dictate specialized solutions. The difficulty for the military establishment arises in deciding when it may be able to get along with cheap and effective commercial solutions, and when it cannot. There may need to be a change of mindset regarding what constitutes a permanent piece of equipment and what may be regarded as a disposable item. The U.S. military recognizes many of these issues, and is pursuing some interesting lines of research into the incorporation of commercial ICT, such as integrating cellular phones into the military environment,[73] and encouraging the widespread development of smartphone "apps."[74] Effective solutions may require new, commercially-inspired technology innovation practices,[75] and further reform in acquisition procedures for ICT.[76] Original and fundamental research may also need to be conducted to create, understand, and manage the full tradeoff space.

[72] BBC (2010)
[73] Dixon et al. (2010); Cheah et al. (2010); DN (2011)
[74] FA53 (2012)
[75] Vassiliou et al. (2011)
[76] Vassiliou et al. (2011); NRC (2010)

Summary and Conclusions

We have identified four "megatrends" reshaping C2 and its associated science and technology. These are:

> (1). The extremely broad availability of advanced information and communications technologies that place unprecedented powers of information creation, processing, and distribution in the hands of almost anyone who wants them—friend and foe alike;
> (2). The increasing complexity of endeavors as military establishments form coalitions with each other, and partnerships with various civilian agencies and non-governmental organizations;
> (3). The rising importance of decentralized, net-enabled approaches to C2; and,
> (4). The data deluge—the unprecedented volumes of raw and processed information with which human actors and C4ISR systems must contend.

These trends interact with each other in various ways. The complexity of endeavors demands complex enterprises, which often operate more effectively in a decentralized, net-enabled manner. Decentralized complex enterprises often generate larger volumes of information than hierarchical ones, contributing to the data deluge. Meanwhile, advanced commercial information and communications technology enables and facilitates both complex endeavors and net-enabled decentralized approaches. It also empowers more actors to create more information, and thus contributes directly to the data deluge.

The four megatrends suggest a number of important priorities for C2-related science and technology, including (in no particular order):

> (1) Facilitating new decentralized, net-enabled C2 in the real world by fully understanding the behavior of people in sociotechnical networks, and understanding how the allocation of decision rights can vary.
> (2) Understanding and alleviating the information conundrum: the observation that the more nimble net-enabled C2 approaches that can be effective in complex endeavors can also generate too many information transactions. How can we fine-tune net-enabled approaches so that enough information is found, processed, and shared to satisfy mission requirements, *and no more*?
> (3) Understanding the enablers and inhibitors of C2 agility.
> (4) Understanding trust in networks.
> (5) Understanding the tradeoffs between on-board processing, transmission, and storage of sensor data. Developing novel methods of automated analysis.
> (6) Embracing commercial information and communications technologies at all possible stages of C4ISR.

There are, of course, many more C2-related S&T topics that deserve attention and some that deserve far more attention that they are currently getting. Our selection of these six areas is not meant to diminish the importance of other C2-related S&T. Rather, in highlighting these six, we believe we have identified those where our improved understanding will enable progress while a lack of understanding will prevent progress. In other words, these topics have make-or-break consequences for the future of new, more effective and agile approaches to C2. In terms of the theme of this the 17th ICCRTS, the pursuit of these S&T topics is on the critical path for “Operationalizing C2 Agility”.

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