A Personal History in System of Systems

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Abstract

The author traces his 50 years of personal experience with computers, communications, and networking (CCN) system of systems (SoS). He provides a perception of how common views of SoS have evolved from strictly technology-based single systems, to pervasive, "stove-piped", programmatic systems, to (not so common views of) SoS, and finally into the realm of "complex" systems. He characterizes the defining, monitoring, management and forecasting of operational properties and boundaries for various example systems from each phase of his career. Insights gained from his experience, mainly expressed in terms of complex systems engineering (CSE) principles, mini-case studies, and SE practices, are offered as a guiding perspective for future complex systems development.

Introduction

To orient the reader, a depiction of the relationships among a system, an SoS, an enterprise, and a complex system, at least as these terms are employed in this paper, is shown in Figure 1. A system (e.g., a laptop) can be viewed as an SoS but an SoS (e.g., GLONASS [Global Navigation Satellite System]) is not always viewed as a system. Similarly, an SoS (e.g., a supply chain) often corresponds to an Enterprise, but an Enterprise (e.g., the U.S. Department of Defense [DoD]) is not necessarily thought of as an SoS. Finally, an Enterprise (e.g., the Ford Motor Company) is usually a complex system, but a complex system (e.g., the auto industry, including the buying public, for instance) is broader than a single enterprise.

Foundational CSE Career Phase

2003-09. The author volunteered to become director of the systems engineering process office for his organization. In this role, among other things, he learned about complexity theory, complex systems,

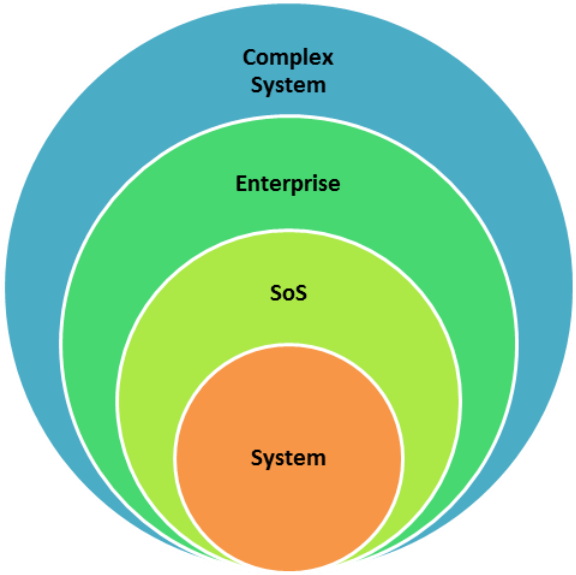

Figure 1. Venn diagram relationships.

and CSE (White 2008) (White 2009). Believing wholeheartedly in these concepts he helped develop some key CSE principles which are purported to work well in "engineering the environment" and addressing the needs of the most difficult systems of our complex world. Some leaders or managers who have been exposed to these principles still resist embracing these ideas, saying, in effect, "Prove to me CSE will work on my project or in my organization." Essentially, these individuals are so risk averse, they are unwilling to even try CSE. Saying "These principles abound and apply very well in nature, and in human languages, for example!", is not enough for them. Thus, there is a need to convince skeptics that CSE is the wave of the future in systems engineering, at least until a "tipping point" (Gladwell 2000) is achieved. The author feels organizations that do not heed this prediction may become less relevant or (a warning) not even survive in the long term.

Defining. A system is often defined as a collection of elements assembled to accomplish a purpose greater than the sum of the functions of its parts (White 2007). The boundary of the system,

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demarking what is inside and what is outside, is open to interpretation; the entity called a system is largely in the mind or eye of the beholder (Martin 2007). Thus, it is often useful to discuss the system's nature, and where the boundary of the system lies, to achieve a consensus of purpose in improving, upgrading, or developing a system to achieve desired operational capabilities. This is key for creating a shared vision of stakeholders.

Although there are variations in SoS types (Baldwin, et al. 2008), an SoS is defined as a collection of systems where each system, established for its own purpose, is managed independently, and is capable of operating by itself in the same environment as the SoS (Maier circa 1996) (White 2007).

CSE is mostly about people who cannot necessarily be controlled or even influenced; it is not so much about technology. CSE is a trans-disciplinary (Sage and Rouse 2009) methodology that leverages a diverse set of disciplines, e.g., psychology, sociology, and organizational change management, in addition to technology. The political, operational, economic, and technical (POET) (Francesca 2009) aspects must all be considered.

Monitoring. When trying to influence a CSE environment, one must watch carefully whether the system is moving in the desired direction. As System Dynamics (Forrester circa 1958) shows this is often extremely difficult because of varying time delays in seeing the results of actions. Part of the CSE art is to help decision makers make better decisions, including how long to wait and when to act.

Management. Self-adaptation and self-organization is a primary characteristic of complex systems. One should not try to force their behavior from the top in a command-and-control, hierarchical fashion typical of conventional systems engineering.

Forecasting. Know that it is essentially impossible to accurately predict the future behavior of a complex system. One can only encourage self-adaptation/organization, letting the system design itself (through trusting the wisdom emerging from constituent interactions) and evolve on its own, while monitoring results and being ready to alter course when deemed appropriate.

Principles of CSE

Here are some principled actions of CSE that will be used to characterize the CCN efforts in connection with enterprise and/or complex (E/C) systems.

1. Bring a healthy dose of personal humility when trying to solve real-world E/C problems.
2. Follow a holistic approach focused on the entire E/C system and the relationships between: a) the system and its environment; and b) the interactions among the components.
3. Achieve a good balance among competing interests across the system instead of trying to optimize any of its components.
4. Utilize trans-disciplinary techniques from psychology, sociology, organizational culture and change theories, etc.
5. Consider and be influenced by the technical aspects of political (P), operational (O), economic (E), as well as [technology] (T) factors.
6. Nurture discussions to learn how people express their concepts using different terms to further mutual understanding and accelerate progress toward shared goals.
7. Pursue opportunity management more than risk management at E/C scales.
8. Formulate heuristics (practical rules of thumb) to assist decision makers.
9. Foster interpersonal and inter-organizational trust by sharing information and acting with honesty and integrity. (Unfortunately, in most organizational cultures; one is usually punished, and only rarely rewarded, for sharing information.)
10. As a governor, leader, or manager create environments to enable interactions of all elements of the E/C system (as opposed to trying to command or control within a top-down hierarchical structure).
11. Stimulate an E/C system to self-adapt and self-organize to enable, evolve, and accommodate change. (Bottom-up solutions in E/C systems are more likely than those imposed from the top. However, one must watch carefully and try to measure what works and what doesn't, and understand why, if possible.)
12. Design, formulate, and certify elements that behave relatively simply. (Sillitto 2010) (This can be a fruitful approach when interactions of these elements yield the requisite complexity, e.g., patterns and emergent behavior.) (McCarter and White 2009)
13. Encourage and develop open, layered architectures that are well-matched to networks comprised of tightly-coupled, highly-interactive elements within each sub-

network, and "loose" inter-connections among the sub-networks. ["Power law" (Various authors circa 2009) behavior mimicking real-world phenomena will result.]

Other Career Phases

In addition to the above CSE Phase that provided the foundation for this paper's SoS analysis, the author's other career phases in CCN systems that will be briefly described and analysed include the following.

- Technical Intelligence
- Satellite Command Link
- Communication to Submarines
- Satellite Band-Pass Limiter
- Bandwidth Efficient Modulations
- Satellite Communications Architectures
- Satellite Multiple Access
- Frequency-Hopping (FH) Radios
- Civil Aeronautical Communication
- Military Global Grid Architecture
- Class of Functions Architecture
- Future Joint Tactical Data Link (JTDL).

Technical Intelligence

1962-65. As a technical intelligence officer, the author studied foreign academic work and science and technology developments with an emphasis on ascertaining progress in CCN-related technologies. As a way to get a 6-12 month lead in the latest open literature, for example, he learned to read scientific Russian and spent time at a research library perusing technical journals before they were translated.

Defining. The main focus of our organization was on space programs. Since this area was being covered adequately by his colleagues, the author chose to examine a few technical areas, e.g., large radio astronomy antennas, high-capacity ferroelectric memories, and a few other CCN technologies, of special interest as a way of ascertaining whether they represented underlying technological leads in military capability.

Monitoring. Regular briefings were offered to local leaders, including senior military officers, and executives of non-profit organizations, and industry. The purpose was to provide an assessment of foreign efforts as progress was tracked. Ironically, once we briefed our material some of the information had already appeared in *Aviation Week*, or other open publications. When someone from the audience would exclaim, "We already know about that!", we would respond rather sheepishly, "Well, we're making it official."

Management. We observed that others were hiding their progress in computer technology from themselves through self-censorship and internal classification. The author thought this was notable because of the huge Western lead in computers at the time, apparently due to our open society and the fact that almost everything about this technology was openly shared in the U.S. It's possible some countries benefited more from reading about U.S. technology than they did from their own shrouded research and development efforts!

Forecasting. It's difficult to predict the future by only trying to extrapolate from history. Thus, the forecasts of our group were not very notable or unexpected. Furthermore, our view of what others had done was quite imperfect, being highly dependent on indirect observations of U. S. scientists or other visitors who tried to report on what they had heard, seen, or surmised, after the fact.

Satellite Command Link

1965-67. During an exciting and challenging assignment in his first "real job", the author worked on a command uplink to a satellite that needed to embody: 1) a simple anti-spoof (AS) authentication function; and 2) a secure pattern, namely, a pseudorandom sequence to control the FH uplink to enhance anti-jam (AJ) performance.

Defining. The command link authentication functionality was quite simple. Suppose there were to be 2^n possible distinct commands. If 64 commands were desired, for example, an n = 6-stage feedback shift register was utilized on the transmit (earth) side. The inverse 6-stage, feed-forward, shift register was allocated to the receiver (satellite) side to minimize any error propagation. The information transmitted consisted of the 6 bits entered into the transmit register which would then "scramble" the bits into a transmitted sequence of 2^n-1 = 63 bits. The inverse shift register would produce the same 6 bits followed by 2^n-1 – 6 = 57 zeroes if there were no errors in transmission. If any other 57-bit sequence was received, the 6-bit command message would be considered invalid, i.e., not authenticated.

An existing timing beacon generator, consisting of a set of shift registers that had relatively prime periods to enable a very long period sequence (consisting of the product of the periods of the individual shift register sequences) but rapid synchronization time (proportional to the sum of the shift register periods) was to be utilized for the AJ portion. The main challenge was to select a combinatorial function that would transform inputs from each of the shift registers to a pseudorandom binary output sequence that would satisfy several properties characteristic of a truly random sequence.

Monitoring. In testing the prototype command link authenticator in the laboratory a timing pulse was inadvertently dropped, and the desired sequence was not transmitted. Observers almost “fell off their chairs” when the receiver authenticated the transmission! It turned out the initial design allowed time shifts of the transmitted sequence to also be legitimate, a serious oversight and negative emergent property. To alleviate this problem of accommodating an occasional missed timing pulse, n had to be increased to allow sufficient “distance” between the possible sequences.

The author was successful in generating FH patterns that seemed to have desirable characteristics akin to random sequences, based on many standard probabilistic run-tests, etc., that he performed.

Management. The work on all aspects of the command link design was presented at a large meeting for a military advisory audience. Although most of the briefings were well-received, the specific approach to creating the hopping pattern caused a problem. One of the agencies in attendance directed the author’s organization to cease work and provide that agency with all the information that was developed, while destroying all related notes, etc..

Forecasting. Apparently this approach, which the author had invented independently, was currently under development by that agency. That this “competition” was indeed the case was learned in a later venue by a colleague who related that fact to the author by happenstance many years later.

Communication to Submarines

1967-69. Another assignment considered modulation and coding techniques appropriate for creating orthogonal waveforms for the Extremely Low Frequency (ELF) submarine communications system (called SANGUINE), where the nominal data rate was only 0.25 bits/second!

Defining. For a relatively simple modulation scheme, Minimum Shift Keying (MSK) has very good power and bandwidth efficiency. The author created MSK waveforms that maximized the number of orthogonal sequences for any sequence length. In the best case, for sequences of powers of two in length, i.e., 2^n, n = 1, 2, 3, …, , he showed how to construct 2^n orthogonal sequences. (White 1973)

Monitoring. Because of the extremely low carrier frequency (45 Hz!), first principles of electrical engineering were applied to advantage. Academic knowledge led the way and “carried the day”.

Management. The SANGUINE project was overseen by a Navy Captain program manager that operated in a fashion similar to that of BGen. Leslie Groves of World War II’s Manhattan Project (Various authors circa 2005). In other words, considering its importance, the program was relatively small and controlled rather tightly; the non-profits and industrial organizations involved either collaborated nicely or did not get to “play”.

Forecasting. One huge, negative emergent property of the SANGUINE buried, distributed transmitter design was the environmental impact. There was so much power to be generated that earth worms would be fried, people/animals might be electrocuted or at least shocked when touching farm fences, and even the moss growing on trees would be affected. Once the local population found out about these potential side effects political support for the project dried up. Eventually, a much smaller above-ground version was implemented.

The lesson learned: system thinking is critical when embarking on such a large project. A board of trustees member pointed this out many years later as an example how non-profit organizations should perform better in addressing such problems.

Satellite Bass-Pass Limiter

1973-74. After a 4-year hiatus spent securing a Ph.D. in Computer Sciences, the author rejoined his former organization and worked on two other interesting efforts. The first was a band-pass limiter design for solving a serious operational problem of high-power earth transmitters unfairly capturing most of the “bent-pipe” capability of a satellite.

Defining. Signal processing techniques (utilizing Fast Fourier Transforms [FFTs]) were employed to reduce the deleterious effects of high power uplink signals. Several algorithms for reducing the larger components in the digital frequency spectrum at the satellite, from clipping to more sophisticated processing, were employed. Unfortunately, these methods only about doubled the number of possible users except when the input signals were close to be synchronized time-wise, an unlikely condition because of the independence of the transmitters.

Monitoring. The author performed self-monitoring mainly utilizing open literature technical papers and textbooks to “flesh out” the basic idea provided to him at the outset of his assignment.

Management. Very little management support was provided and working conditions were abnormal for the organization, e.g., the author did not even have a desk for the first few weeks after reporting for work, and had to operate off a tea cart!

Forecasting. This investigation resulted in a conference paper but to the author's knowledge none of the techniques were implemented on-board satellites.

Bandwidth Efficient Modulations

1975-76. In his later effort bandwidth efficient modulation methods developed by the author proved to be much more effective. This allowed frequency division multiple access (FDMA) uplinks to be much more closely packed together (due to lower "crosstalk") saving considerable uplink bandwidth.

Defining. Various time-domain shapings of the modulation signal improved considerably on the properties of MSK from the point of view of end-to-end signal processing. The x-dB bandwidths and "splatter" of the transmitted spectrum were largely irrelevant. This learning was a positive emergent property of this ground-breaking work. (Reiffen and White 1978)

Monitoring. This work enjoyed considerable support from at least one knowledgeable and powerful outside source. Naturally, this motivated the author to redouble his efforts in exploring this area.

Management. There were at least two notable occasions when the project managers overseeing and encouraging the work were delighted by the findings.

Forecasting. Several technical journal articles and conference papers resulted. The concepts strongly influenced the design and development of an important military satellite system that is still in use today.

Satcom Architectures

1977-79. Although the author changed organizations, he continued working in military satellite communications (Satcom).

Defining. The main topic was satellite architecture. There were two basic schools of thought, one favoring a three-segment architecture, consisting of tactical, strategic, and intelligence satellite systems operating in the UHF, EHF, and SHF frequency bands, respectively; and a two-segment architecture.

The other tension was the relative importance of the earth terminal segment vs. the space segment.

Monitoring. The importance and high cost of the satellite system programs rated attention of upper management both within DoD and the participating organizations, viz., non-profits and other contractors.

Management. The program was driven by the politics of the space segment organization, at least from the point of view of the terminal segment organization with which the author was associated. The various technical trade-offs seemed to be weighted in favor of the space segment instead of creating potential solutions that balanced the relative costs of the terminal and space segments.

Forecasting. The main challenges were in the technologies and cost of the EHF portion of the architectures. This involved a relatively new frequency band that had more bandwidth but that was more susceptible to propagation disturbances such as rain, dust, and oxygen absorption. A couple of crucial questions centered on whether EHF technology was mature enough and/or affordable.

Satellite Multiple Access

1979-81. The author studied various types of multiple access techniques, random access (RA), including Aloha and Slotted Aloha; Demand Assignment Multiple Access (DAMA); FDMA; Time Division Multiple Access (TDMA); and Code Division Multiple Access (CDMA). A hybrid was advocated, where the specific access scheme utilized would adapt to the amount of traffic loading.

Defining. RA techniques such as Slotted Aloha (accurate time to a fraction of a slot is required but twice the peak performance is achieved) work well on lightly loaded channels. DAMA is preferred for moderately loaded channels. If the channel traffic is extremely heavy, TDMA is usually preferred. CDMA is practical for a moderately large number of users but performance is sensitive to the "near-far" problem if a few received user signals are much more powerful than others.

Monitoring. This was a relatively new but "hot" area of satellite communications. As such there was a fair amount of scepticism and some reluctance to provide support. The author got into some trouble with his department management after he hired his very first employee to help in this network control area. The candidate had mislead the author as to his credentials and proved to be incompetent. The author worked with this employee for three years and helped him co-author and present a paper at a conference, This was all for naught, as the employee was recruited away during this conference, and left the organization for another, shortly thereafter!

Management. Managers were willing to listen to the espoused ideas but they gave most of their attention to the more pressing issues of satellite system architecture.

Forecasting. Even at that time it was clear that military network control was an important topic for the future. In later years this concern devolved into the mantra for network-centricity that emulated and leveraged the power of the internet.

Frequency Hopping (FH) Radios

1986-1993. After five years with a private small business, the author contributed to several important communications projects after returning to his prior organization. First, he led two projects in FH radio development.

Defining. The thrust of one project was to increase the carrier FH rate by about two-orders of magnitude to defeat a "repeat" jammer that would try to detect and jam the current frequency before the system radios hopped to the next frequency. A widely used existing radio family was being upgraded and standardized to accommodate this new design.

The other project was focused on developing an AJ and AS radio that would be interoperable with a family of ground radios. Unfortunately, in this case the contractor was not thoroughly vetted (There was even grass growing up in their parking lot!), and they ultimately failed to deliver. After a painful "witch hunt" within the author's organization, the contract was finally terminated for the convenience (and considerable cost) of the government!

Monitoring. The principal problem of the first project was observing, analyzing, and assessing the technology necessary for constructing a reasonably effective repeat jammer. One friendly country had been selling radio and jamming-capable equipment to any country willing to buy. At least one such country was viewed as a potential adversary, so that was not a good thing!

Management. International cooperation and collaboration was required among the "five power" nations to reach agreement on the hopping rate. That took considerable effort but was ultimately successful. However, the DoD controlled the algorithm that determined the hopping pattern and that was not shared with the teaming nations. These failures of communication and diplomatic protocol seriously delayed an important program.

Forecasting. One never really knows the identity of future adversaries. In those days the concern was solely in terms of nation states, not loosely affiliated terrorists as in world of 2010.

Civil Aeronautical Communication

1993-1997. Then the author was assigned to the civilian domain and became centrally involved in a design effort and subsequent standards development of a new all-digital voice and data radio for pilot-controller communications called VHF Digital Link Mode 3 (VDL-3) and an Automatic Dependent Surveillance - Broadcast (ADS-B) capability, both for the civil aeronautical domain.

Defining. The main thrust of VDL-3 was a new digital modulation scheme for significantly increasing the communications capacity of the existing 25 kHz bandwidth channels within the VHF aeronautical frequency band. At the same time, the amount of co-channel and adjacent channel interference had to be limited.

ADS-B permits all equipped aircraft crews to "see" surrounding aircraft on their cockpit displays for heightened situational awareness without having to totally rely on air traffic controllers; thus, the controllers can serve as backup.

Monitoring. These activities had international air traffic management implications so new standards had to be developed and agreed upon.

At first VDL-3 was primarily a U.S. effort. Attention had to be paid to what the Europeans were doing within their airspace to address their even more serious capacity short-fall. Time pressure led to them sticking with the usual analog radios (upgraded for greater frequency stability, however) and introducing yet another channel spitting "bandaid" fix that this time resulted in only 8.33 KHz bandwidth channels.

ADS-B had a competing waveform, being pushed by Sweden (although a U. S. company was operating behind the scenes) called VDL Mode 4.

Management. Two series of VDL-3 meetings, one within RTCA, and later with the International Civil Aviation Organization (ICAO), over several years, was required to develop the international standard for an agreed-to digital waveform for both voice and data communications. The RTCA meetings were initially quite contentious between the two-sides; but agreement on a good waveform was ultimately achieved. Because of the hard work accomplished within RTCA, the ICAO meetings were relatively efficient in adopting the standard. Two of the author's personal contributions proved to be key factors for success in created the new standard: 1) explanation of the equivalence of two different definitions of inter-channel interference resolved a fleeting controversy with a U. K. colleague; and 2) a detailed written description of the waveform that answered all other questions.

All publically-listed participants in the ADS-B standards development were subsequently vilified in the press by one individual for allegedly creating a vulnerability that could be exploited by terrorists. He said we all should have been incarcerated in Ft. Leavenworth! Clearly, ADS-B can be turned off as required, e.g., during military maneuvers.

Forecasting. Unfortunately, the VDL-3 ICAO standard has not yet been implemented. Insufficient attention was paid to economic issues that 1) alienated the airlines who would have to equip with new radios; and 2) embarrassed the service providers who had not budgeted for the required ground radios.

The U. S. version of ADS-B, called the Universal Access Transceiver (UAT), is catching on worldwide after being successfully tested in the very challenging Alaskan airspace (Various authors 2009).

Military Global Grid Architecture

1999-2002. Following a two-year assignment as a resource manager of task leaders in a new matrix organization, the author re-joined his previous communications/networking division and became project leader of "Global Grid Architecture".

Defining. Several alternative multi-layered communications and networking (C&N) architectures were proposed and analyzed during this project. Many protocols were allocated to different layers. This laid out multifarious options and clarified how a system could evolve to increase C&N performance by improving the implementation within any layer without disturbing the implementations of other layers provided the interfaces between layers remained simple and relatively constant.

Monitoring. There was an effort to influence other development projects and sell them on the advantages of utilizing a layered architecture. Gradually, over several years, this idea caught on to a great extent, e.g., within a large software-defined-radio program. [Refer to Future Joint Tactical Data Link below.]

Management. This project was overseen by a tactical C&N program manager and his chief engineer, both of whom had a very practical modus operandi. They were not research oriented but did encourage and recognized good technical work that would led to increased C&N capabilities.

Forecasting. Several specific thrusts for improving C&N performance were advocated by the author and his team, viz., localized processing among Unmanned Air Vehicles (UAVs), directive antennas on, and antenna pointing control among, "wide-body" aircraft, and improved mobile routing algorithms. Unfortunately, none of these suggestions have come to fruition. Although budgetary shortfalls have been cited as an inhibitor, it is more likely that these innovative ideas were not properly sold.

Class of Functions Architecture

2003. The author was instrumental in defining and selling a class-of-functions approach to airborne C&N architecture, as opposed to the usual platform-centric approach that leads to an N^2 problem of pair-wise information exchanges that is untenable because: 1) N is very large, in the order of 65; and 2) too many requirements must be updated continually, an unrealistic proposition because human resources are typically not available for such bookkeeping.

Defining. Certain aircraft, particularly the wide-bodies employ similar functionalities. Common realization of at least some of these implemented sub-systems would improve not only efficiency but perhaps effectiveness, as well. In addition, the N^2 problem could be solved by adopting the net-centric best practice where each platform concentrated on getting into and out of the airborne network, instead of trying to accomplish pair-wise information exchanges with all other platforms in the network.

Monitoring. The customer organization was duplicative with many committees pursuing similar aims to improve interoperability and "horizontal" integration of the airborne network. This would have been okay except there was too little interaction among the groups; thus, the best ideas were not shared and built upon. Also, little progress was made toward influencing the program offices of record to do more than merely continue trying to "vertically" integrate their stove-piped programs unabated.

Management. Intra-organization cooperation and collaboration was lacking. Another problem was an inter-organizational rivalry which muddied the waters as to which organization was responsible for what.

Forecasting. Effective long-term progress was hindered by the continual changes of the officer in charge as these individuals moved through the organization leaving different management "footprints" as they sought their next promotions. Not surprisingly, true network centricity for such networks is still a future goal.

Future Joint Tactical Data Link

2010. Just before leaving his corporation, the author's last two C&N assignments were in reviewing: 1) the status of an airborne software-defined radio program; and 2) an aerial (new name, replacing "airborne") network and making recommendations regarding a future Joint Tactical Data Link (JTDL).

Defining. Achieving good performance in aerial networks, which generally include not only aircraft but also satellites and some ground terminals, is very challenging. This is largely because such networks rely mainly on wireless C&N. Many types of aircraft have very narrow bandwidths that limit nominal communication data rates to about 1 Mb/s or less at L-band, and about 10 kb/s or less at UHF, for example. So far, at least, programs for developing directive antennas, e.g., phased-arrays, on "wide-body" aircraft, that would greatly increase possible data rates and provide increased AJ and long probability of intercept (LPI) performance, have not received sufficient funding. (Refer to Military Global Grid Architecture—Forecasting above.)

Monitoring. Layered C&N architectures are facilitating effective and efficient performance and are providing flexibility for modifying the implementation of any given layer for future improvements. It's good news that the airborne software-defined radio program architecture is essentially layered.

A combination of error-detection and forward-error-correction helps mitigate the loss of communication packets. But single-cast packet transmissions still dominate, and up to a 30% packet loss is not unusual with current procedures. Thus, there is a need to improve multi-cast algorithms.

Periodic field exercises are held to experiment with new C&N techniques aimed at achieving network-centric capabilities, in general, and achieving time-critical targeting requirements, in particular. A key capability of net-centric operation is the ability to redirect already en route aircraft to alternative targets.

Fortunately, modern time budgets reflect a relaxation of earlier constraints (which had been in the order of only seconds) placed upon C&N, considering that aircraft flight times (typically tens of minutes) dominate the overall time budget. Also significant is human decision-making time (typically minutes) in authorizing an attack.

Management. Progress is evidenced by a greater emphasis on portfolio management, i.e., a concerted effort to oversee a "basket" of individual ("stove-piped") programs. Here the intent is to give greater emphasis on the collective capabilities of the portfolio, and eliminate poorly performing programs.

Sadly, people are still trying to control the operational performance of the network by "brute force", something that is doomed to failure in such a complex environment where uncertainty reigns.

Forecasting. Future trends need to include self-adaptive and self-organized networks because it is impossible to predict how these future communications networks will need to be employed.

Another powerful initiative would be to perform more processing locally and transmit only what is needed by recipients. However, recipients will accept this change only if there is a higher degree of mutual trust in the sources of information.

In addition, a greater use of Binary eXtensible Markup Language (XML) (greatly eliminating metadata) would reduce the amount of necessary data transmitted by two orders of magnitude!

Summary and Conclusions

The author's impressions of which CSE Principles applied to each aspect (Defining, Monitoring, Management, and Forecasting) of the operational properties and boundaries of the CCN projects he supported and cited in his long career are noted in Table 1 by **Pn**, where n corresponds to the n^{th} principle. A principle that should have been applied and was not, is shown in parentheses and in red, as **(Pn)**, to accommodate readability of black and white prints. In addition, every row of Table 1 is characterized by either a full set, or a subset, of the **P5** Poet factors. Each short phrase in the table is intended to remind the reader of the essence of the discussion in the main body of the paper associated with that table cell.

The reader may not be able to discern any general trend with respect the proper application of the CSE Principles, even after studying the table. However, only two projects appear to have escaped unscathed from any CSE Principles that should have been applied, viz., Bandwidth Efficient Modulations, and Future JTDL. The author remembers the first of these as a time of creative career recovery; conditions were good! The second and most recent experience bodes well in further exploring CSE principles in developing and implementing future self-adaptive and self-organizing networks that can benefit all. Principle 12, mentioned only once in the table (under Satellite Command Link), should play a key role in the future.

References

Baldwin, K., et al., "A Model of Systems Engineering in a Systems of Systems Context," CSER, Redondo Beach, CA, 4-5 April 2008.

Forrester, J.W. “System Dynamics,” circa 1958, http://en.wikipedia.org/wiki/Jay_Wright_Forrester.

Francesca, M., “Integrating POET,” 2009 MITRE Innovation Exchange, McLean, VA, 5-7 May 2009, http://www.mitre.org/news/events/exchange09/9.html,

Gladwell, M., *The Tipping Point: How Little Things Can Make a Big Difference*, Little, Brown and Company, 2000.

Maier, M. W., “Architecting Principles for Systems-of-Systems,” circa 1996, http://www.infoed.com/Open/PAPERS/systems.htm.

Martin, J. N., “Systems are Imaginary—Systems are Not Real: Some Thoughts on the Nature of Systems Thinking,” INCOSE International Symposium, San Diego, CA,

McCarter, B. G., and B. E. White, “Emergence of SoS, sociocognitive aspects,” chapter three in *Systems of Systems Engineering—Principles and Applications*, M. Jamshidi, Ed., CRC Press, Boca Raton, FL, 2009, pp. 71-105.

Reiffen, B., and B. E. White, “On Low Crosstalk Data Communication and its Realization by Continuous-Frequency Modulation Schemes,” IEEE Transactions on Communications, Vol. COM-26, No. 1, January 1978, pp. 131-135.

Sage, A. P., and W. B. Rouse, *Handbook of Systems Engineering and Management*, 2nd Edition,Wiley, New York, 2009.

Sillitto, H. G., “Design Principles for Ultra-Large-Scale (ULS) Systems,” INCOSE International Symposium, Rosemont, IL, 12-15 July 2010.

Various authors, “ADS-B,” circa 2009, http://en.wikipedia.org/wiki/Automatic_dependent_surveillance-broadcast.

Various authors, “Manhattan Project,” circa 2005, http://en.wikipedia.org/wiki/Manhattan_Project.

Various authors, “Power Laws,” circa 2009, http://en.wikipedia.org/wiki/Power_law.

White, B. E., “On the Construction of *N-ary* Orthogonal Sequences Under a Continuous-Phase Constraint,” IEEE Transactions on Information Theory, Vol. IT-19, No. 4, July, 1973, pp. 527-532.

White, B. E., “Systems Engineering Lexicon,” Taylor and Francis Complex and Enterprise Systems Engineering Book Series web site, 2007, http://www.enterprise-systems-engineering.com/lexicon.htm.

White, B. E., “Complex adaptive systems engineering,” 8th Understanding Complex Systems Symposium, University of Illinois at Urbana-Champaign, IL. 12-15 May 2008, http://www.howhy.com/ucs2008/schedule.html.

White, B. E., “Complex Adaptive Systems Engineering (CASE),” IEEE Systems Conference, Vancouver, Canada, 24 March 2009.

Biography

Brian E. White received Ph.D. and M.S. degrees in Computer Sciences from the University of Wisconsin, and S.M. and S.B. degrees in Electrical Engineering from M.I.T. He served in the U. S. Air Force, and for 8 years was at M.I.T. Lincoln Laboratory. For 5 years Dr. White was a principal engineering manager at Signatron, Inc. In his 28 years at The MITRE Corporation, he held a variety of senior professional staff and project/resource management positions. He was Director of MITRE's Systems Engineering Process Office, 2003-2009. Dr. White retired from MITRE in July, 2010, and currently offers a new consulting service, CAU←SES (“Complexity Are Us” ← Systems Engineering Strategies).

Table 1: Summary of CCN system characteristics (including CSE principles)

CCN Program	**Defining**	**Monitoring**	**Management**	**Forecasting**
Technical Intelligence **P5: POET**	Politically dominated but with special topics **P6**	Internally processed intelligence vs. open literature data **P2,P7**	Dearth of information sharing **(P9, P10) P11**	Historical projections and **(P1)** information tidbits
Satellite Command Link **P5: POT**	Innovative designs **P2, P3, P12**	Emergent property uncovered in testing **P1, P10 (P11)**	Inter-organizational "squabble" **(P6, P9)**	Project was "shut down" **(P7, P10, P11)**
SANGUINE **P5: POT**	Exploratory analysis and synthesis **P1**	Electrical engineering fundamentals **P10**	Lean with tight control **P7**, **P11**	Failure to foresee public repercussions **(P2)**
Satellite Band-Pass Limiter **P5: POT**	Exploratory analysis **P1, (P2)**	Self-monitoring through literature **P7**	Non-existent **(P4)**	Only factor-of-two gain in performance **P10**
Bandwidth Efficient Modulations **P5: OT**	Time-domain shaping, analysis, and simulation **P6**	Considerable outside interest **P9** motivated the work	Engaged oversight and encouragement **P10**	Results influenced future satellite **P11** system development
Satcom Architectures **P5: POET**	Two purposeful architectures for **P1** three user segments	High-level oversight was prevalent **P5, P7**	Politically driven by control organization **(P3,P6,P9,P10)**	EHF cost was large uncertainty **P2, P5: E**
Satellite Multiple Access **P5: OT**	Burgeoning topic with ample multiple access schemes **P8**	Early adopters were actively pursuing techniques **P3, P6**	Stakeholders listened but were not enthusiastic **(P10)**	Networking evolved along with success of internet **P7**
Frequency-Hopping (FH) Radios **P5: POT**	Hopping rates, FH algorithms, and interoperability **P2, P6**	FH technology and foreign military sales **P1, P3**	Autocratic locally but constructive progress team-wise **P9, P10**	Technology driven but need diminished as Wall came down **(P11)**
Civil Aeronautical Communication **P5: POET**	Strong negotiations involving technical issues **P3, P6, P9**	Influence of important stakeholders **P1, P2**	Competitive, collaborative, and insightful **P10, P11**	Economic interests were incompletely addressed **(P5: E)**
Military Global Grid Architecture **P5: POET**	Matrix of many protocols mapped to architectural layers **P2, P13**	Layered architectures finally caught on **P6, P7**	Informed, practical, and stimulating **P2, P10, P11**	Forward looking ideas were not sold to decision makers **(P5: E, P8)**
Class of Functions Architecture **P5: POET**	Innovative approach to more effective airborne networking **P2, P3**	Several duplicative committees not talking to each other **(P4, P6)**	Inter-organizational rivalry confused the roles and missions **(P9)**	Network-centric progress slowed by command changes **(P10, P11)**
Future Joint Tactical Data Link (JTDL) **P5: POET**	Means for increased data rates are well understood **P1, P2, P3**	Layered C&N architecture and experimentation **P13**	Program portfolio and ad hoc distributed networks **P6 , P7**	Self-adaptive and self-organized networks **P9, P10 P11**

Pn = nth CSE Principle that applied, if in **black** font; or should have been applied, if in parentheses (..) with **red** font

P = Political; O = Operational; E = Economic; T = Technical