Science and Technology Development for Communications and Distributed Systems at APL

Robert L. Holland Jr.

This article characterizes the state of science and technology (S&T) development for communications and distributed information systems (referred to henceforth simply as distributed systems) at the Laboratory as determined by a review of related efforts described by several APL staff members during presentations to the Senior Leadership Team. A context for the discussion is provided by considering the nature of current and future communications and distributed systems supporting the exercise of command and control for the DoD. In addition, examples of significant, ongoing APL communications and distributed systems programs are discussed. Finally, those communications and distributed systems S&T initiatives presented to the Senior Leadership Team are summarized, and conclusions and recommendations regarding the state of such S&T efforts at the Laboratory are offered.

PREFACE

Science, Technology, and Systems Engineering

To set the stage for what follows, it is worthwhile to take a moment for a brief philosophical diversion to discuss the notions of science, technology, and systems engineering and their relationship to one another. This special issue of the *Technical Digest* is devoted to exploring the current state of science and technology (S&T) development and understanding at the Laboratory. At the same time, APL is renowned as a premier systems engineering resource, so at least a rudimentary appreciation of the relationships among science, technology, and systems engineering will help us to understand more completely the significance and relevance of the discussion hosted in this issue.

For the purpose at hand, I draw upon a terse and clever discussion of science and technology provided by the English embryologist Ian Wilmut, who found it necessary to address this subject in his recent book describing the process he and Keith Campbell have used to clone mammals.[1] In summary, according to Wilmut, “technology is about changing things . . . altering our surroundings to make our lives more comfortable and to create wealth,” whereas “science is about understanding how the universe works and all the creatures in it.” Although these statements are not in any sense rigorous, they will suffice for our discussion. Likewise, Wilmut is careful to make the observation that science and technology can, and have, existed as separate and independent entities. However, he is likewise quick to point out that both thrive when they are mutually supportive, and this is an essential observation for us. Examples abound, like the boost given to the biological sciences by the visions of microscopic life first provided by light microscope and later by electron microscope technologies, and the deep design insight given in return to the microscope technologies by the sciences of optics and electron diffraction.

Drawing from this discussion that it is best for the enhancement of both science and technology that their developments are tightly coupled, what then can be said about their relationship to systems engineering? For this purpose I offer the following definition: systems engineering is a creative process using science to develop formal solutions to practical problems and then aggregating and integrating technologies to create the "systems" that implement those formal solutions. It is implicit in this characterization of systems engineering that the best systems engineers are those well informed about contemporary sciences and technologies, if not direct contributors to one or both. It often happens, of course, that when faced with the complexities associated with the solution of complex, "real world" problems, systems engineers are confounded by the lack of suitable sciences and related technologies required for their systems solutions. At such times, they must enter into a dialog with scientists and technologists in hopes of inspiring S&T breakthroughs of relevance to their practical problem. In the end, then, the systems engineer appears as a third player in the advancement of S&T, serving not only to consume the fruits of S&T, but also to inspire scientists and technologists to pursue work with guaranteed practical interest. So, as a natural extension of Wilmut's characterization of the symbiotic relationship between science and technology, one is led to recognize an essential and mutually beneficial trialogue among practitioners of science, technology, and systems engineering which has as its unifying theme the development of practical solutions through the application of one or more sciences and technologies.

It is not unusual at APL for these communities of scientists, technologists, and systems engineers to be very tightly bound, serving day to day to advance the interests and achievements of each community and thereby serving our sponsors most effectively.

Communications and Distributed Systems

The notion of a *distributed system* used for this discussion is contained in the following definition: A *distributed system is a collection of autonomous, physically separated computers and concomitant transceivers (each computer–transceiver pair is a system "node") connected for information transfer by data links and provided with distributed application software.*

A distributed system of this general nature is illustrated in Fig. 1 in which *N* distinct nodes are shown and connectivity between the various nodes is achieved by the establishment of a total of *M* communications links between node pairs. The computers serve as data processing, storage, and display platforms, and each associated transceiver provides the ability to transmit and receive information via the data links; i.e., the transceivers support information transfer between node pairs of the distributed system. Because our definition includes the information transfer (i.e., communications) component, the following discussion simply addresses distributed systems, with the understanding that suitable, associated communications systems are distinct and essential components of the distributed systems.

The scope of this discussion is limited by considering, in particular, those distributed systems devoted to implementing command and control (C2) functions for various components of the DoD. This limitation is not too severe, since it includes nearly all of those distributed systems with which APL has been associated throughout its history, and the ultimate, relevant S&T characterizations apply equally to significant non-DoD distributed systems with which the Laboratory has been associated. As illustrated in Fig. 2, a distributed system supporting DoD C2 functions will, in general, allow the cognizant commander to exchange information with sensor and logistics systems and with forces capable of delivering weapons to targets. The distributed system supporting the commander's connectivity with these force elements is once again represented as a collection of computer and transceiver nodes; however, it is important to note that this collection of nodes is generally heterogeneous, requiring a number of hardware and software solutions that guarantee interoperability despite the component heterogeneity.

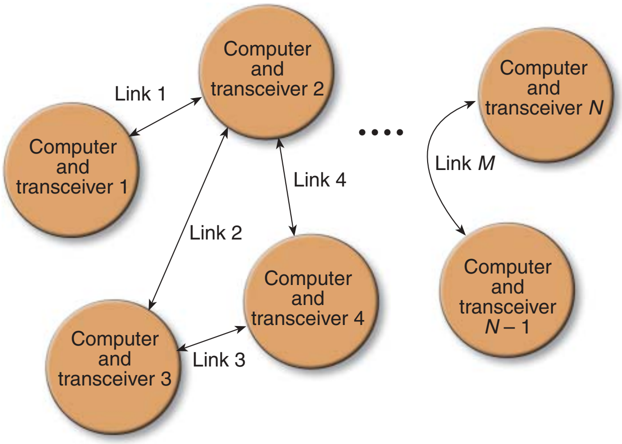

Figure 1. Distributed system nodes and links.

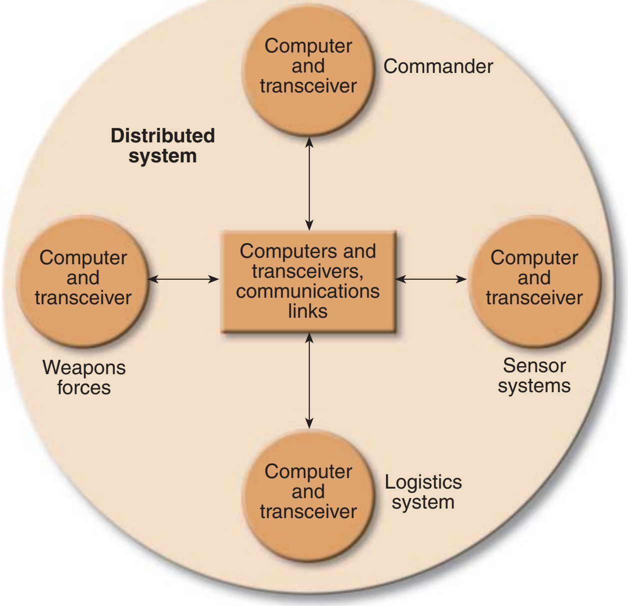

Figure 2. Distributed systems for DoD command and conrol.

DISTRIBUTED SYSTEMS FOR DOD COMMAND AND CONTROL

Current Systems

Of great relevance to this discussion is an understanding of the nature of current and future DoD distributed systems. Today, distributed systems supporting DoD C2 functions constitute an ensemble of service-unique, special-purpose, disconnected systems. This circumstance is illustrated in Fig. 3, which shows that each service currently has its own subnetwork domain within which isolated, special-purpose tactical subnetworks are established to support special-purpose C2 needs; indeed, to date, virtually all such DoD C2 subnetworks have arisen from a specific, isolated requirement and not as the result of an overarching, unifying plan for implementing requisite C2 functions. Despite more than a decade of focus on interservice interoperability, it is also true that information is rarely exchanged between service-specific distributed systems. Finally, the Defense Information Systems Network (DISN)—established and maintained by the Defense Information Systems Agency (DISA) as the consolidated, worldwide, enterprise-level telecommunications infrastructure providing end-to-end information transfer for the DoD—is essentially disconnected from the tactical service networks.

Future Systems

Despite these circumstances, the DoD has defined a vision and set a course to implement its distributed system of the future. That system, known as the Global Information Grid (GIG), is envisioned as an "information environment comprised of interoperable computing and communications components."[2] Specifically, the GIG is intended to be a globally interconnected system-of-information systems for collecting, processing, storing, disseminating, and managing information for warfighters, policy makers, and support personnel. Known before 1999 as the Global Information Infrastructure, the GIG has recently gained renewed emphasis within the DoD as the key enabler of network-centric warfare and is now assigned to the Office of the Assistant Secretary of Defense for Command, Control, Communications, and Intelligence (OASDC3I) for the specification of requirements and oversight of development and fielding.

The DISN plays a central role in the GIG information transfer architecture. Whereas tactical subnetworks must provide the infrastructure for local area networks (LANs), campus area networks (CANs), and

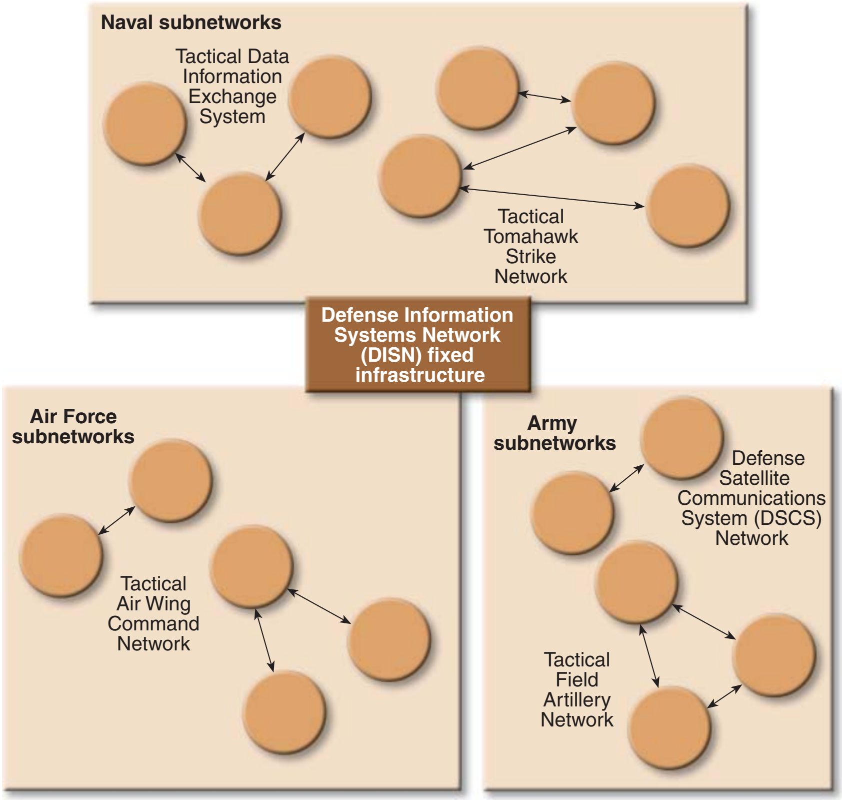

Figure 3. The current state of operational DoD distributed systems.

operational area networks (OANs), the DISN is identified as providing the wide area network (WAN) and metropolitan area network (MAN) infrastructure for the GIG. In addition, DISN communications services such as the Secret Internet Protocol Router Network (SIPRNET) are also to be provided to the tactical forces. Of course, this description of the role of the DISN in the GIG implies a substantial degree of connectivity between tactical networks and the DISN that does not exist today.

Movements within each of the services suggest that they are preparing to address the need to configure their tactical subnetworks as components of the GIG. Within the Navy, the concept of the FORCEnet has arisen as the unified foundation for Navy C2. FORCEnet's implementation directly supports the realization of Navy network-centric operations.[3] The description of FORCEnet in Ref. 3 is accompanied by a description of the Expeditionary C5 Grid (EC5G), a collection of Navy strategic and tactical communications networks that will provide the underlying information transfer for FORCEnet. At the same time, the CNO Executive Board has advocated the creation of a central authority to manage and operate the naval network infrastructure as the maritime components of the GIG.

The Army and Air Force are likewise developing distributed system concepts to achieve a unified foundation for C2. Under the aegis of the Future Combat System (FCS) for the transformed force, the Army is developing new C2 concepts and methods as well as allied communications network architectures. The Air Force is making similar advancements in association with efforts devoted to the realization of a distributed system for C2 called the Battlespace Infosphere.

Figure 4 illustrates the objective of the GIG. In this high-level representation of the future GIG architecture, each service has so evolved its component subnetworks that information exchange is possible among them as well as among various subnetworks of the other services. In addition, direct connectivity with the DISN is implemented. The subnetwork interfaces illustrated in Fig. 4 are notional, since the extent to which actual subnetworks are connected depends on the evolving service C2 architectures as well as the overarching requirements of the GIG. As an illustration of FORCEnet features, the figure anticipates that, in its role of enabling fire support of land forces from the sea, the Naval Fires Network C2 distributed system will require the provision of real-time data descriptive of the status of collaborative Tactical Tomahawk strikes. Likewise, the illustrated mechanism for establishing connectivity between otherwise independent nodes of the GIG is the use of gateways that serve as "protocol transformers." Some of the component subnetworks of the GIG may well arise from new system developments and may therefore emerge as interoperable by design. However, for the foreseeable future, the majority of GIG subnetworks will likely be legacy networks for which interoperability is most readily achieved through the development and application of suitable gateways.

Engineering the GIG

Much work has yet to be done to realize the GIG illustrated in Fig. 4. Not the least of the achievements required is the articulation of a C2 concept of operations and allied architecture that is consistent with the ability to gather and distribute information globally and to include tactical units as providers and recipients of

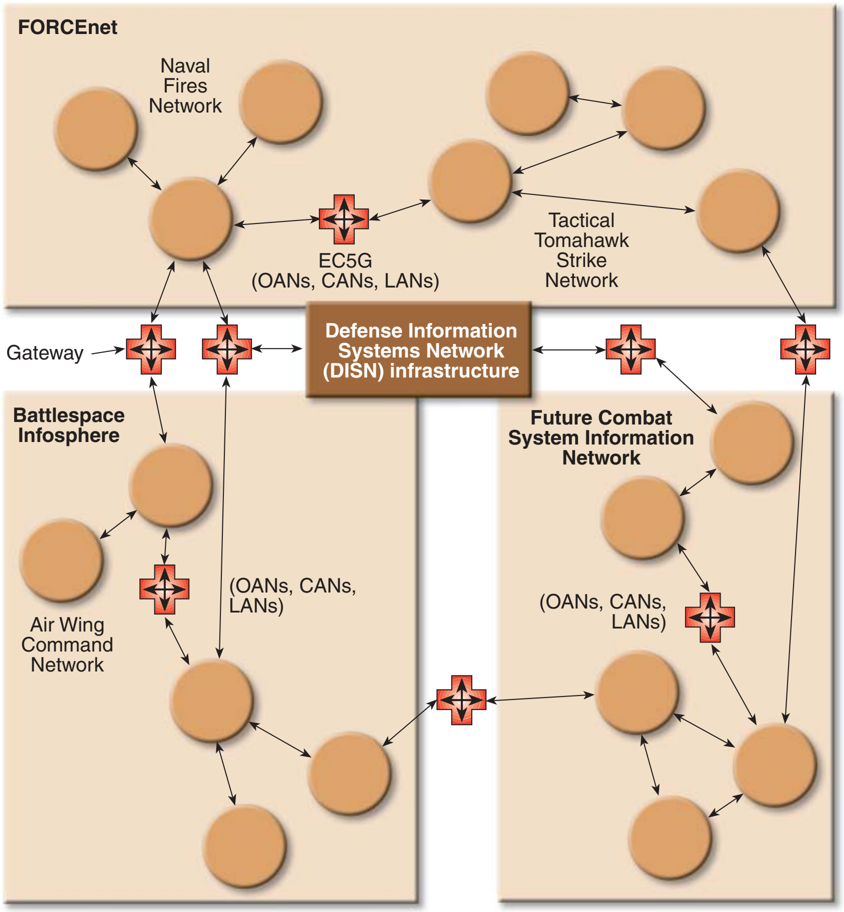

Figure 4. Global Information Grid objective.

that information. Such C2 concepts must also account for a significant increase in the ability of joint and coalition tactical forces to establish direct (i.e., “horizontal”) connectivity. The detailed character of any C2 architecture will strongly depend on data acquisition, processing, display, and storage technologies available to support command decision making and information distribution management.

In addition, the details of the GIG information transfer infrastructure (the network-of-networks architecture, including network control mechanisms) must be addressed. Each armed service must consider the configuration of legacy network resources or the development of auxiliary network resources and systems (e.g., gateways) to provide components of the LANs, CANs, and OANs capable of delivering DISN services to tactical warfighters. The OANs present a formidable near-term problem since they will be required, in most instances, to establish interfaces with other service OANs and networks established by coalition forces in addition to establishing the tactical side of DISN interfaces. At the same time, new tactical subnetworks will continue to emerge in response to special warfighting requirements and will have to be designed from their inception with the ability to interoperate with other networks—a practice that simply has not been followed to date.

Finally, DISA must implement enhancements or extensions to the DISN so that it can readily support the delivery of services to the tactical forces via the OAN interfaces. In this regard, it is important to realize that the requirement to provide DISN services directly to tactical forces is a very recent development.

DISTRIBUTED SYSTEMS S&T AT APL

Programs

The history of distributed systems development at APL goes back at least as far as the 1960s and the TRANSIT system, which was a critical component of the distributed system whose elements were Poseidon ballistic missile submarines. A selected set of recent APL programs devoted to the development of distributed systems is listed in Table 1. The table gives lead and supporting departments for each program. Summary descriptions of four of these distributed system programs are provided to illustrate their nature, diversity, and significance.

Table 1. Selected APL distributed system programs.

New and continuing programs	Lead department	Supporting departments
Cooperative Engagement Capability (CEC)	Air Defense Systems	Power Projection Systems
Ship Self-Defense Mk II	Air Defense Systems	
Continuing Evaluation Program	Power Projection Systems	
DSCS Integrated Management System (DIMS)	Power Projection Systems	
Tomahawk Strike Network	Power Projection Systems	
Multifunction Buoyant Cable Antenna	National Security Technology[a]	Power Projection Systems
DD-21	Power Projection Systems	Air Defense Systems
National Missile Defense	Air Defense Systems	Strategic Systems, Joint Warfare Analysis, Power Projection Systems
SPAWAR Technical Direction Agent	Power Projection Systems	
DoD Teleports	Power Projection Systems	Space
Future Combat System Architecture	Joint Warfare Analysis	Air Defense Systems, Research and Technology Development Center, Power Projection Systems
FAA System Engineering	Power Projection Systems	Air Defense Systems
Polar 2 and 3 EHF Communications Payload Control	Power Projection Systems	Space
CONTOUR, MESSENGER, STEREO	Space	Power Projection Systems

[a] Formerly Submarine Technology.

Cooperative Engagement Capability

This well-known APL program provides a quantum improvement in the ability of a battle force to defend itself from airborne threats by distributing raw radar data from organic shipboard radars to all battle force elements and then developing the same composite target tracks for each battle force element. In terms of our distributed systems model, the CEC system achieves this functionality using computing platforms (i.e., Cooperative Engagement Processors [CEPs]) on each battle force element to manage the distribution of that element's radar data to other battle force elements and to develop composite target tracks from the radar data received from other battle force elements. In addition, the CEC uses a unique transceiver system (the Data Distribution System) onboard each participating combatant to establish anti-jam, high-capacity, line-of-sight connectivity with neighboring combatants. In most distributed systems the processing tasks and products of the various system computers are related but not identical; however, the CEC distributed system is characterized by the fact that the objective of each CEP is to execute the same composite track generation algorithm and to produce exactly the same product (set of composite tracks) at each system node.

Defense Satellite Communications System (DSCS) DSCS Integrated Management System (DIMS)

The DIMS is a hardware/software suite being developed by APL for installation in 13 DSCS Operations Centers (DSCSOCs) worldwide. DSCSOC personnel perform a variety of functions necessary to provide planning and management for all DoD networks established using the DSCS satellites as relays. The DIMS dramatically simplifies the DSCSOC network planning and management process by establishing interfaces with 10 legacy DSCSOC subsystems, providing for automated data transfer among them (before DIMS, such data transfer was done manually), and establishing a single station where all of the subsystems can be monitored and controlled. An essential feature of the DIMS is that of supporting the exchange of DSCS network status information among all DSCSOCs. Thus, in terms of our distributed systems model, the DIMS distributed system computers reside in each DSCSOC with transceivers that provide inter-DSCSOC connectivity via commercial, terrestrial fiber networks and DSCS wartime reserve satellites. In this case, while the tasks performed by the DIMS computers are essentially the same (although capable of unique tailoring at each site), the products are typically distinct, reflecting the unique DSCS network status at each DSCSOC.

Tactical Tomahawk Strike Network (TSN)

The TSN will establish a communications network whose network terminals include those aboard in-flight Tactical Tomahawk missiles; at least one "strike manager" network terminal will reside on ship or ashore. APL has played a central role in the development of the TSN—from originally demonstrating the utility of satellite communications to provide in-flight connectivity with missiles to the development of network control strategies and strike manager decision aids. Implementation of the TSN will allow message exchanges with the missiles during a strike, the passage of missile health and status information from the missiles to the strike manager, and the delivery, if necessary, of mission modification messages from the strike manager to the missiles. The ability to exchange such messages with Tactical Tomahawk missiles during a strike will provide unprecedented real-time insight into the overall status of a strike as well as alternative and/or updated targeting information to each missile. In terms of our model, the TSN distributed system includes a collection of computers onboard in-flight missiles that generate and transmit missile health and status information and receive and process mission modification messages. The missile systems also include transceivers that establish connectivity with the strike manager via DoD ultra-high-frequency communications satellites.

DoD Teleports

The DoD Teleports program has direct relevance to the implementation of the GIG. The purpose of the program is to deploy a collection of teleports worldwide in three phases (through 2010) to function as gateways allowing the delivery of DISN services to tactical forces. Since the tactical forces may be deployed to almost any part of the globe, they will continue to depend heavily on their satellite communications systems. Thus, an essential feature of each teleport will be a complement of satellite communications terminals, including terminals accessing all DoD and some commercial communications satellite constellations. In addition, each teleport will include a complex of baseband equipment necessary to initiate or terminate the myriad individual tactical links that must be managed and a collection of switches and routers required to handle message traffic at the DISN interface. Finally, each teleport must establish connectivity with the various DoD satellite communications network control entities to allow the establishment of satellite communications links when necessary.

During an APL-led analysis of alternatives for this program, the teleport architecture (the number of teleports required and their placement around the world) was derived; the Laboratory is currently the System Integrator for the first-phase deployment of the teleports scheduled for completion at the end of FY2003. Follow-on phases of deployment must account for the fact that all DoD and most commercial satellite communications systems will undergo substantial changes in their space, terminal, and control segments during the next decade. In addition, the commercial communications infrastructure (the primary DISN backbone) will evolve, and the DoD satellite communications network control structure is scheduled to be unified over the next 10 years. Thus, each significant teleport interface will be evolving.

In terms of our distributed systems model, the DoD Teleports serve as an enabling mechanism to provide DISN services to the distributed system comprising tactical C2 systems. Significantly, these teleports constitute the first realization of the gateways required in the GIG illustrated in Fig. 4; i.e., the teleports will provide the gateways for connectivity between the service subnetworks and the DISN. In that sense, then, APL is already helping to engineer the GIG.

Distributed System Functions Map to Related Sciences and Technologies

We now look more closely at our elementary distributed systems model and add some useful detail about a set of generic functions that must be performed to realize the desired information processing and dissemination features of such systems. This brief diversion yields a convenient and powerful means by which to categorize representative APL efforts devoted to distributed systems S&T. More importantly, however, the discussion provides insight into those aspects of distributed systems directly affected by these representative APL S&T developments.

Figure 5 illustrates three nodes of a generic distributed system, two of which comprise the familiar computer and transceiver nodes (labeled 1 and *N*), and another computer and transceiver pair that functions as a network switching or routing device, or as a gateway when nodes 1 and *N* reside in different networks. The illustration is augmented, however, by the addition of a listing of distributed system functions segregated at the highest level into C2 application functions, computing functions, and communications functions. The computing functions are listed more specifically as information processing, storage, and display. The communications functions are listed more specifically as (in ascending order) physical layer through application layer functions. This latter characterization of communications functions is a derivative of the well-known Open Systems Interconnect reference model often cited in data networking treatises.[4] The left side of Fig. 5 aggregates the computing and communications functions, while the right side illustrates that some of the essential communications functions are (usually) actually executed as algorithms within the computing platforms at each node.

Typically, the C2 applications residing at each of nodes 1 and *N* must exchange (digital) data to serve their intended purpose. Thus data must flow from the computer at each node to its transceiver, and the transceiver uses the data to generate related electromagnetic signals that propagate in the communications medium. Likewise, the transceiver at each node receives electromagnetic signals in the physical medium (generated at other nodes) and passes the derived information to the computer at that node.

Each of the communications functions (also called "protocols") listed is codified in an algorithm, realized in software or firmware, and has been developed over the past three decades to ensure that the passage of

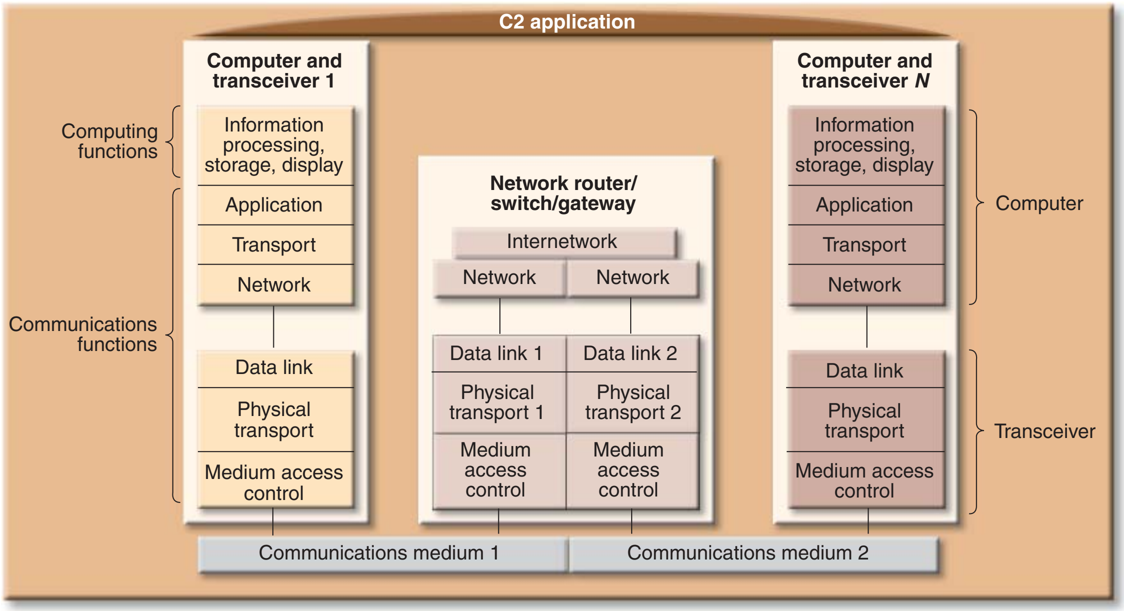

Figure 5. Distributed system functions per node.

data from one node to the other is reliable, efficient, and, to a large degree, independent of the types of computers in use at each node and the detailed structure of the intervening network. These protocols are implemented concurrently at any pair of nodes of the distributed system that are exchanging data. Each communications protocol exchanges information with its peer protocol at the other node; i.e., some of the data exchange between two communicating nodes directly supports the execution of the protocols and is distinct from any C2 application data that are transferred. In addition, of course, each protocol provides services to the local protocols (immediately above and below it in Fig. 5) that directly facilitate the passage of C2 application data between the nodes. Thus, the *medium access control protocol* implements services necessary to guarantee that all participating nodes can efficiently share (i.e., transmit and receive signals in) the same communications medium (usually subject to both power and bandwidth constraints). The *physical transport protocol* provides those services necessary to generate and receive signals suitable for propagation in the communications medium. The *data link protocol* provides services that convert communications medium signals to digital data streams and vice versa, implements channel coding and decoding, and ensures that data are successfully transferred from one node to the next node in the network (e.g., from node 1 to the closest network router in Fig. 5). The *network protocol* provides services that deliver data from the source node to the destination node across some subset of the entire collection of network nodes. The *transport protocol* ensures that data delivered to the destination node are properly ordered and error-free. It also initializes the establishment of connectivity between the nodes when data transfer is required. Finally, the *application protocol* provides data format conversions if necessary and implements any source coding/decoding and encryption/decryption required.

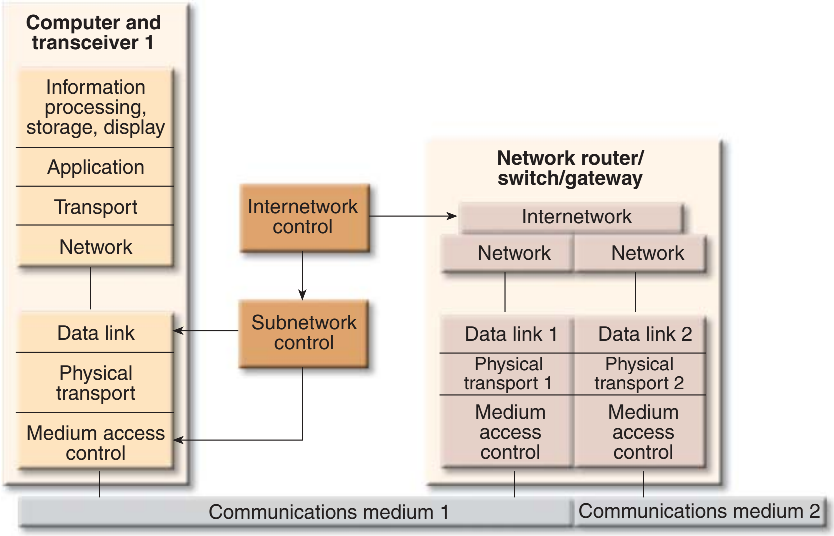

Figure 6. Internetwork and subnetwork control functions.

Figure 6 depicts two additional protocols of importance in most DoD communications networks: *subnetwork control* and *internetwork control*. The subnetwork control protocol allows for centralized management of access to the communications medium for all participants within a subnetwork; information exchanges involving the nodal data link, medium access control, and subnetwork control protocols are typically necessary to effect the desired centralized access control. The internetwork control protocol provides centralized management of communications medium access and subnetwork-to-subnetwork connectivity for the entire information infrastructure of the distributed system.

For our purpose here, note that each distributed system function discussed is directly associated with a class of related sciences and technologies. Thus, when considering APL S&T initiatives devoted to distributed systems, we can categorize them by identifying the distributed system protocol they implement or support. At the same time, we are able to appreciate more fully the depth and breadth of APL's contributions in light of the full spectrum of distributed systems elements.

Survey of Distributed Systems Sciences and Technologies

APL technical departments responded to a call from the Science and Technology Council for presentations to the Senior Leadership Team illustrating the state of S&T at the Laboratory in several domains, including distributed systems. Here, a summary overview of the resultant distributed systems S&T developments is presented. The boxed insert contains presentation titles and identifies APL staff members who delivered the associated presentation; all S&T achievements are categorized by the associated distributed systems protocol implemented or supported.

In almost all cases, the sciences and technologies presented by the participating departments were inspired by the need or ability to significantly enhance the performance of existing systems, although many of the S&T developments described are directly applicable as components of newly developed systems for the future.

Physical Transport Layer

Physical transport layer sciences and technologies reported consist of unique antenna developments and

APL DISTRIBUTED SYSTEMS S&T PRESENTATIONS

- Physical Transport Layer
  - *Multifunction Buoyant Cable Antenna*
    - G. R. Thompson
  - *Two-Way Submarine Global Star Communications at Speed and Depth*
    - R. E. Ball
  - *Advanced Antenna Technology*
    - R. C. Schultze
  - *Solid State Power Amplifier Technology*
    - J. E. Penn
- Data Link Layer
  - *Advanced Transceiver Systems*
    - M. J. Reinhart
  - *Turbo Codec Software Radio*
    - M. A. Jordan
  - *Turbo-Coded Continuous Phase Modulated Signaling*
    - R. E. Conklin
- Internetwork and Subnetwork Control Layer
  - *Quality-of-Service (QOS) Based Networks for DoD Communications*
    - S. D. Jones
  - *Resource Allocation for Heterogeneous Networks*
    - I. Wang
  - *Time Division Pair-Wise Access (TDPA) Network Control*
    - J. M. Gilbert
- Application Layer
  - *Wavelet Compression Video*
    - Q. E. Dolecek
- Computing System Layer
  - *Joint Composite Tracking Network (JCTN) Concept Assessment*
    - S. W. Kay
- Command and Control Application Layer
  - *Interoperability and TBMD Communications*
    - M. D. Sapp
  - *Homelink Telemedicine System*
    - J. G. Palmer
  - *Navy Telemedicine 1996–2001*
    - R. L. Stewart
  - *Coordinated Autonomous Operation of Multiple Unmanned Vehicles (UAVs)*
    - H. E. Gilreath

power amplifier design; i.e., S&T pertinent to the generation and receipt of communications channel signals. G. R. Thompson's presentation, *Multifunction Buoyant Cable Antenna*, and R. E. Ball's presentation, *Two-Way Submarine Global Star Communications at Speed and Depth*, described antenna technology developments applicable to providing satellite communications for submarines without requiring movement to periscope depth. R. C. Schultze's presentation, *Advanced Antenna Technology*, described an inflatable reflector technology that provides reliable, low-cost, high-gain, circularly polarized antennas for spacecraft. And J. E. Penn described the development of reliable, efficient, high-throughput solid-state amplifiers for use in space-qualified systems during a presentation entitled *Solid State Power Amplifier Technology*.

Data Link Layer

Data link layer sciences and technologies included advanced transceiver systems, a software radio, and an investigation of a contemporary coding and modulation scheme; i.e., sciences and technologies relevant to the generation and demodulation of communications channel signals and channel encoding/decoding. M. J. Reinhart's presentation, *Advanced Transceiver Systems*, described advanced transceivers for spacecraft applications that preserve performance while becoming smaller, lighter, and more power efficient. M. A. Jordan's presentation, *Turbo Codec Software Radio*, described the development of a software radio implementing a turbo coder/decoder to verify the ability of turbo codes to provide increased power efficiency in narrowband satellite communications channels. And R. E. Conklin's presentation, *Turbo-Coded Continuous Phase Modulated Signaling*, described an effort aimed at combining the bandwidth efficiency of continuous phase modulation with the power efficiency of turbo codes, with the goal of finding ways to choose coding and modulation parameters that provide predictable bandwidth and power efficiency.

Internetwork and Subnetwork Control Layer

Internet and subnetwork control layer sciences and technologies presentations included research devoted to aspects of internetwork management strategies and the description of a subnetwork control structure being implemented to enable the distribution of CEC data. S. D. Jones' presentation, *Quality-of-Service (QOS) Based Networks for DoD Communications*, described a concept for real-time negotiation with multiple subnetwork control entities to access subnetwork resources necessary to establish and maintain QOS-based information flows across the (typically heterogeneous) subnetworks. In a related effort, I. Wang's presentation, *Resource Allocation for Heterogeneous Networks*, described algorithms developed to combine and schedule information flows to make optimal use of resources available from multiple, heterogeneous subnetworks. Finally, J. M. Gilbert's presentation, *Time Division Pair-Wise Access (TDPA) Network Control*, described the subnetwork control strategy supporting the TDPA-based information exchange characteristic of CEC; this allows the establishment of a TDPA network for a collection of nodes whose number and location are originally unknown while minimizing the latency of information delivery throughout the network.

Application Layer

The application layer technology presentation described a unique means of achieving data compression of video data streams. In *Wavelet Compression Video*, Q. E. Dolecek reported on wavelet-based compression/decompression algorithms optimized for use with his wavefront array processor. These algorithms have the potential to achieve a 50:1 reduction in the data rate required to transmit "good quality" video imagery.

Computing System Layer

The computing system layer technology presented was a software application used to characterize the performance of contractor-developed proprietary software products. In a presentation entitled *Joint Composite Tracking Network (JCTN) Concept Assessment*, S. W. Kay discussed software developed to provide a means of benchmark-testing candidate JCTN tracking algorithms in an effort to identify those worthy of further, more formal testing and potential development by the government.

Command and Control Application Layer

The C2 application layer sciences and technologies discussed exhibited a common theme: the specification of strategies for the integration of multiple distributed systems technologies in the service of unique C2 requirements. In *Interoperability and TBMD Communications*, M. D. Sapp described enhancements to existing Navy Battle Force Management C2 Infrastructure (BMC2I) components necessary to guarantee adequate performance for a class of future operational missions, including Tactical Ballistic Missile Defense. The resulting class of recommended enhancements provides the Navy with guidance and supporting rationale pertinent to funding decisions for preplanned product improvements for the BMC2I. J. G. Palmer's presentation, *Homelink Telemedicine System*, described an effort that led to the integration of contemporary computing and communications technologies for an outpatient monitoring and medical regimen management system to provide acute medical intervention for chronic conditions, including congestive heart failure. Such quality out-patient care is currently unavailable. R. L. Stewart's presentation, *Navy Telemedicine 1996–2001*, described the specification and integration of multiple, pertinent shipboard and land-based medical diagnostic and communications system technologies to provide deployed Navy aircraft carriers and amphibious ships with access to land-based medical expertise and facilities. In his presentation, *Coordinated Autonomous Operation of Multiple Unmanned Aerial Vehicles (UAVs)*, H. E. Gilreath described an effort to define, simulate, and demonstrate a distributed system architecture for the command and control of a team of UAVs with sensor and communications payloads; the objective of this effort is to enable the provision of ubiquitous, tactical airborne sensors controlled by tactical warfighters.

CONCLUSION

Current Status

For nearly 40 years, the Laboratory has made significant contributions to programs resulting in the development and deployment of distributed systems in support of national security objectives. Today, APL is continuing that tradition with involvement in a wide variety of such programs, including national programs supporting the development of Navy and Army service information infrastructures (including several specific subnetworks) and the GIG. In support of these system developments, APL is also engaged in significant, associated S&T development efforts. Clearly, our ability to identify the need for and to perfect such S&T contributions is a strong function of and, typically but not exclusively, related directly to our many systems engineering efforts for significant DoD distributed systems developments.

On the other hand, the Laboratory has little or no association with a number of significant DoD distributed systems programs. With regard to distributed systems sciences and technologies in particular, we are making no contributions to some domains (e.g., the transport and medium access control layers). Even in those domains to which we contribute, we are far from exhausting the potential for additional, significant efforts. Since most APL distributed systems S&T efforts are directly related to programs for which systems engineering for distributed systems is the Laboratory's central responsibility, association with a more extensive array of development efforts would likely expand our repertoire of distributed systems S&T initiatives. Of course, given the limited availability of precious internal research and development funding, the validity of this hypothesis largely depends on the willingness and ability of our distributed systems development sponsors to fund allied S&T development tasks, a practice that is less common now than in previous years as system developers must often concentrate more on near-term objectives to field those systems on schedule.

Future Directions

To position ourselves to continue and expand our distributed systems and related S&T contributions, we must maintain cognizance of the numerous and rapidly mutable programs and allied systems devoted to DoD C2 and communications networks. For example, after having defined the future military satellite communications architecture (relevant to the time span from 2006 through 2020) following many years of deliberation during the 1990s, the DoD has very recently declared its intention to review that architecture and consider possible, radical departures, including the deployment of an entirely new constellation of communications satellites, known as the Transformational Communication System (TCS), to serve special strategic forces; opportunities abound to participate in the redefinition and development of such future military satellite communications systems.

In addition, especially within the domain of distributed systems, it is likewise necessary to maintain cognizance of pertinent commercial computing and communications sciences and technologies, services, and standards. Whereas stunning achievements within the commercial computing and communications domain are now commonplace and therefore of great interest for possible application to DoD system solutions, it is also true that these commercial systems are rarely developed to be consistent with DoD system requirements. It therefore becomes necessary to understand well both the commercial distributed systems technology developments and DoD system requirements in order to make wise use of those technologies for DoD systems. We must be ready and able to provide guidance to our DoD sponsors in this regard and be prepared to make wise choices of commercial technologies for inclusion in our DoD distributed systems designs. For example, the commercial trend toward the convergence of communications and computing infrastructures has immense implications for DoD distributed systems architectures, assuming that such a convergence makes sense for the warfighting systems.[5]

One trend that is clear from the descriptions of the GIG is the movement toward an ever more complex DoD information transfer infrastructure. The ability to analyze and model such complex networks will become critical to the development of associated system solutions. Hence, the Laboratory can position itself to play a more substantial role in the design of future DoD distributed systems by enhancing our ability to analyze and test such complex networks. It must be acknowledged from the beginning, however, that characterizing these complex networks is no trivial task; recent efforts to develop high-fidelity models of Internet communications performance are still mostly the realm of university researchers, and it is not yet clear, in general, how to specify the initial conditions for such models.

The need for continued development of sciences and technologies for each of the distributed systems protocols will remain strong. For example, at the physical transport layer, there is an ongoing need in numerous DoD distributed systems developments for antennas that exhibit one or more of the following properties: conformal, compact, multiband, and multibeam. At the data link layer, the push toward more radio-interconnected combatants, including the emergence of autonomous, robotic participants, continues to stress limited bandwidth and power resources available for DoD communications, so the need for ever more bandwidth and power-efficient modulation and coding schemes will continue. The movement toward more complex (often, gateway interconnected) networks brings with it the added requirement of more effective and efficient subnetwork and internetwork control protocols. In addition, the advanced C2 decision aids required to make the best use of the flood of information that such complex networking will deliver to DoD decision makers will continue to require more capable data processing, storage, and display technologies and more advanced distributed applications.

Finally, the Laboratory is intent upon and well known for providing end-to-end systems engineering solutions. To be positioned to do so for the development of distributed C2 systems for any specific application (warfare) area, APL must participate in the development of the initial, associated C2 concepts of operations, architectures, and derived system requirements. Any rational distributed C2 system development approach must select specific computing and communications system components from among myriad possible choices by requiring system performance that is consistent with the fundamental C2 strategy selected.

REFERENCES

[1] Wilmut, I., Campbell, K., and Tudge, C., *The Second Creation: Dolly and the Age of Biological Control*, Harvard University Press, Cambridge, MA, pp. 9–11 (2000).

[2] *Global Information Grid (GIG) Capstone Requirements Document*, JROCM 134-01, CDR Executive Agent, Commander-in-Chief, U.S. Joint Forces Command, C4 Plans, Policies and Projects Division (J61) (2001).

[3] *Network Centric Naval Forces, A Transition Strategy for Enhancing Operational Capabilities*, Naval Studies Board, National Research Council, National Academy Press, Washington, DC, pp. 140–174 (2000).

[4] Piscitello, D. M., and Chapin, A. L., *Open Systems Networking*, Addison Wesley Press, New York, pp. 33–45 (1993).

[5] Messerschmitt, D. G., "The Prospects for Computing-Communications Convergence" in *Proc. Vision 21: Perspectives for Information and Communication Technology Conf.*, Munich, Germany (1999).

ACKNOWLEDGMENTS: Insight into the state of S&T for communications and distributed systems at APL would not have been possible without the devotion and sacrifice of those staff members who, while very busy with the press of ongoing work, composed and delivered the presentations for the Senior Leadership Team that are summarized here. I am indebted to them for their singular efforts.

THE AUTHOR

ROBERT L. HOLLAND Jr. is a member of the Principal Professional Staff and Supervisor of the Information Transfer Group of APL's Power Projection Systems Department. He received a B.S. in electrical engineering from the University of Colorado in 1970, and an M.S. in applied physics from The Johns Hopkins University in 1975. He is a member of the Tau Beta Pi, Sigma Tau, Eta Kappa Nu, and Sigma Pi Sigma honor societies. Mr. Holland joined APL in 1970 and has spent the majority of his professional career engaged in communications system engineering for applications as diverse as command and control for deployed Pershing missiles and in-flight connectivity via satellite communications for Tomahawk missiles and Predator unmanned aerial vehicles. He served as the plenary speaker for the Communications and Distributed Systems presentations to the Senior Leadership Team. His e-mail address is robert.holland@jhuapl.edu.