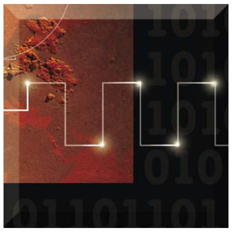

Communications for the Warfighter: Research and Development at APL

A. Roger Hammons Jr., Jack L. Burbank, Steven D. Jones, Ross E. Conklin, Naim M. Merheb, Michael A. Jordan, William T. Kasch, Jerry R. Hampton, and Julia Andrusenko

In the DoD vision of the Global Information Grid (GIG), the warfighter becomes an edge node in a seamless internetwork comprising the entire warfighting enterprise. The communications challenges posed by the GIG vision of network-centric warfare are diverse and far-ranging. APL is committed to helping solve these challenges through its focused research and development efforts. Recent efforts highlighted here include propagation studies to characterize radio transmission in military RF bands; studies regarding the best military use of commercial off-the-shelf technologies; studies of advanced channel coding, including turbo codes and space-time codes, to increase the efficiency of wireless links; and studies of adaptive spectrum use and cross-layer design to optimize the radio to prevailing conditions.

INTRODUCTION

The military community is currently redefining how wars will be fought in the future. The resulting "transformation" is moving toward "network-centric operations," wherein the force fundamentally relies on the communications network. This transformation to a network-centric fighting force is predicated on the ability to achieve an Internet-like network capability in operational areas through the Global Information Grid (GIG) currently under development.

Previous military communications systems have frequently been highly efficient networks that provide a very specific type of service to a specific application in a specific environment. However, these systems, often based on proprietary or government-specific technology and rigidly defined performance requirements, suffer from poor interoperability with other systems, the inability to accommodate technology insertion, and inflexible security policies, even while applications evolve.

The GIG vision poses diverse and far-ranging communications challenges. APL is committed to helping solve these challenges through focused research and development efforts based on a systems engineering approach and on the Laboratory's expertise in military systems.

COMMUNICATIONS NEEDS OF THE WARFIGHTER

The ongoing transformation of the military toward an information-centric fighting force places unprecedented importance on the GIG-connected communications systems available to the warfighter. The network-centric warfare paradigm and GIG vision are based on the ability of the communications network to deliver, at any time and any place, the right information to the right users with the required performance and security characteristics. For the new paradigm to be effective, the communications systems for future forces must satisfy the following:

- Be quickly deployable and mobile so that force structure deployment and/or maneuver timelines are not dependent on the deployment of communications systems. The systems must support communications "on the move" and allow users to be addressed independent of location.
- Be highly available and interoperable so that information can be sent to and from anywhere at any time.
- Require minimal configuration. When the soldier turns it on, it must work.
- Allow for future technology insertion, so that the network can be adapted to meet changing warfighter needs.
- Be highly flexible in order to adapt to changing mission and user needs, providing quality of service (QoS) to the user as needed. QoS metrics include latency, capacity, and error rate.
- Be able to adapt to changing channel conditions autonomously.
- Provide efficient communications with sufficient bandwidth to support information-intensive tactics and maneuvers.
- Provide sufficiently secure communications to enable dominance in the information space.
- Be easily sustainable, requiring minimal logistical and support structure.
- Be cost-effective.

Note that many of the assumptions upon which existing commercial technology is based do not hold in the military environment. The military communications problem is unique in the wide variety of communications scenarios that it covers. Units may be located on the ground, at sea, under the sea, and in the air. They may be near population centers or isolated behind enemy lines. In the battlefield, resources such as bandwidth are scarce; notions of fixed nodes, base stations, and even population centers do not necessarily exist; and the networks are targets of aggressive physical and electronic attacks. Protection of classified information is also of vital concern.

Warfighters must have access to the information required to complete their mission. In the GIG, QoS is a necessity, not a business decision. The monetary penalties typically imposed in the commercial domain for failure to meet negotiated QoS guarantees have no military counterpart. Consequences in the military setting may include the loss of human lives. The GIG environment requires an approach to QoS that works from source to destination and is compatible with the security protections applied to the messages being transmitted. Depending on location, mission, and application, the performance required from the communications network may differ.

APL COMMUNICATIONS R&D

The R&D efforts at APL seek to make important contributions to critical challenges—such as the communications challenges to the GIG vision posed by transformation—based on a systems engineering approach. Recent efforts include propagation studies to determine the fundamental characteristics of radio transmission environments; studies of how best to use commercial off-the-shelf (COTS) communications technologies in the battlefield; studies of advanced channel-coding techniques, such as turbo codes and space-time codes, to increase the efficiency of wireless communications links; and studies of adaptive spectrum use and cross-layer design to adapt and optimize the radio to prevailing conditions. Highlights of representative APL efforts are presented below.

Propagation Studies

Over the past several years, the U.S. military has dramatically increased its participation in urban warfare and peacekeeping missions. This trend is likely to continue into the future.[1,2] The Army's Future Force Program predicts a greater demand for communications connectivity and bandwidth in a diverse set of environments. The growing focus on the GIG and on network-centric warfare implies the need to accurately predict communications performance in the tactical battlefield, particularly in an urban setting. For this, communications engineers need validated propagation models to plan and design communications systems. Unfortunately, most urban propagation models focus on commercial applications involving elevated base stations operating at commercial frequencies (approximately 900 and 1800 MHz), which provide little guidance for military communications systems.

Communications is one of the biggest challenges for military operations in urbanized terrain (MOUT). Different building types, foliage, furniture, windows, doors, people, traffic, and street geometries are only a few of the many factors that can contribute to the degradation of a radio signal. The APL-funded MOUT project investigated the applicability to the urban warfare scenario of two current military tactical communications technologies: the Single Channel Ground and Airborne Radio System (SINCGARS) and squad radios. Both operate in the 30- to 88-MHz frequency range,[3] for which there are few existing RF propagation prediction methods.

Since the majority of military tactical communications systems have been tested in open spaces with clear lines of sight (e.g., a desert environment), there is a lack of available measured data and validated prediction models indicating what type of signal degradation (path loss) one should expect in an urban setting. Indoor propagation models are particularly lacking in either availability and/or proven fidelity.[2]

To address these needs, APL has developed a hardware suite representative of the SINCGARS radio (Fig. 1) and has used it as a test bed for indoor and outdoor propagation measurements on the APL campus. Based on these measurements, new analytical path loss models have been developed for indoor and outdoor RF propagation. Figure 2 shows an example of path loss measurements at 30 MHz taken inside a typical one-story office building. In the figure, these data are compared against the path loss predictions achieved by various APL models under development.[2,4,5] The new models provide significant improvement over existing commercial-band models extrapolated to the 30- to 88-MHz band.

Figure 1. MOUT receiver setup.

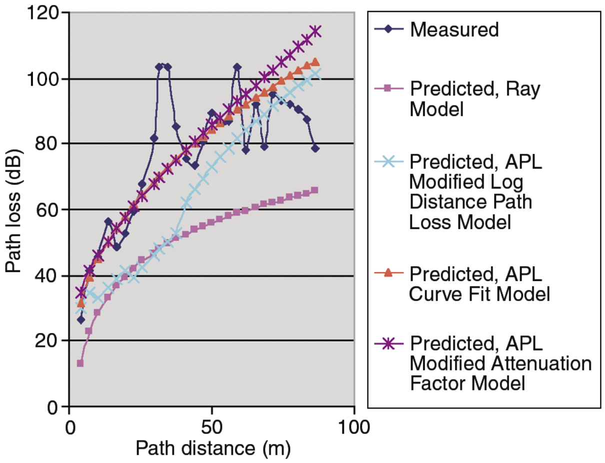

Figure 2. Different path loss models at 30 MHz for a one-story office building. Model predictions of hallway path loss show various degrees of fidelity compared with representative measurement data.

Similar propagation studies for outdoor urban environments have been conducted by APL under Independent Research and Development (IR&D) funding. The effort has focused on tactical urban communications between ground-based communicators in the military UHF band (225–450 MHz). The open literature has little information on propagation effects in this regime. Experimental measurements using an APL-designed test bed were taken in an urban canyon setting (i.e., where buildings are much taller than either the antenna heights or the RF wavelengths). Philadelphia was chosen for its flat terrain and rectangular street geometry. Extensive data sets were collected to determine propagation attenuation as a function of path distance for different combinations of RF frequency, antenna height, street geometry, and street width. Figure 3 presents representative results of measured path losses versus distance for both open and urban terrain. As shown in the figure, the measured open terrain data agree closely with standard open terrain path loss models, and curve fits of the urban terrain data show the promise of an APL urban-terrain path loss model under development.

Leveraging COTS Technologies

The design of future tactical communications systems is heavily based on technologies and techniques that make up today's commercial network infrastructure. This strategy of taking advantage of COTS technology has many potential benefits across the acquisition life cycle. Since the commercial domain can achieve a much greater economy of scale than its more specialized DoD counterparts, the COTS strategy can lower system costs significantly. Although the military's desire to leverage commercial practices as much as possible is understandable, commercial technologies and techniques are not designed primarily to meet military needs, and thus may not be well suited for this application.

APL continues to be involved in a variety of activities to facilitate the successful integration of COTS technology into military applications while attempting to characterize and minimize the associated drawbacks.[6,7] This includes continued involvement in commercial standards activities, such as the Internet Engineering Task Force, as well as the development of new concepts and test beds.

The APL Adaptable Channel Test bed for Investigating On-the-move wireless Nodes (ACTION) is one example. As illustrated in Fig. 4, ACTION is a comprehensive testing platform for analyzing the performance of commercial wireless local area networks (WLANs) with mobile nodes. It provides a controlled simulation environment to model mobile nodes as they move through a cellular-like network area by manipulating the dynamic characteristics of the signals emitted and

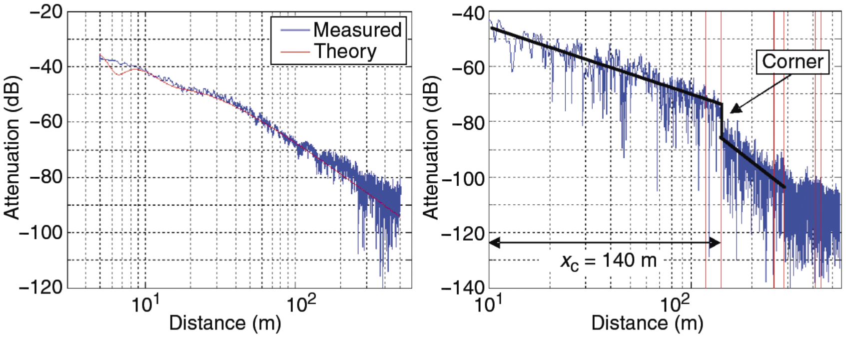

Figure 3. Comparison of path loss versus distance measurements in open and urban terrain. (Left) Path loss measurements in open terrain correspond to theoretical models in the literature. (Right) Path loss measurements in urban terrain are fitted to an APL model under development.

received by a mobile node. The hardware and software devices (amplitude, phase, and frequency controllers [APFCs]) that control and change these signal components form the heart of ACTION. Network analysis software collects statistics on packet errors, bit errors, and link availability.

ACTION has been used to determine the network performance of high-speed projectiles using IEEE 802.11b radios for the Two-Way Robust Acquisition of Data (2-RAD) program. The objective of 2-RAD was to define an architecture for a cost-effective ground network capable of providing high-speed connectivity to a variety of mobile platforms, including high-speed projectiles equipped with miniaturized radios. The Army's Yuma Proving Ground (YPG) in Arizona implemented a WLAN infrastructure in 1996 using COTS equipment that conformed to the IEEE 802.11b WLAN standard. Cisco Aironet 340 series wireless bridge products (i.e., base stations) provided the WLAN backbone and coverage for mobile platform connectivity. APL furnished initial coverage predictions for the YPG 802.11b implementation[8] and developed ACTION to model parts of this predicted coverage area as well. Results were used to predict behavior for an on-site field test to demonstrate a proof of concept of the 2-RAD IEEE 802.11b architecture. The field test was performed with a Hydra rocket moving at up to Mach 2. (For additional details on the 2-RAD program, see D'Amico and Lauss, this issue.)

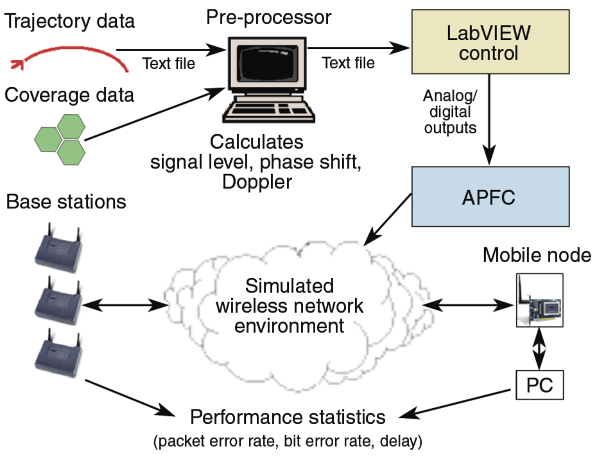

Figure 4. The APL ACTION test bed.

Advanced Channel Codes for Satellite Communications

Channel codes are critical to the design of a satellite communications system because they allow the system to perform and operate reliably at the low signal levels typical of satellite links. Communications systems use channel coding to translate a stream of information bits into symbols suitable for transmission across a channel in such a way that, after decoding, any errors introduced by the channel can be identified and corrected with high probability. In principle, channel coding would allow the system to achieve information transmission rates arbitrarily close to the ergodic capacity of the channel. Well-known examples of error-correcting codes for the additive white Gaussian noise (AWGN) channel include binary convolutional codes, algebraic Reed-Solomon codes, and, most recently, turbo codes. The discovery of turbo codes[9] in the early 1990s revolutionized communications theory by exhibiting a practical channel coding technique that could in fact deliver near–channel-capacity performance. This achievement was so remarkable that it was initially greeted with much skepticism within the communications community.

APL was the first proponent of the use of turbo codes for military satellite applications. Detailed performance studies[10] were conducted for the new Advanced Extremely High Frequency (AEHF) system, a multibillion-dollar military satellite communications system. Since the AEHF has particular features that are not typical of most communications systems, APL developed a high-fidelity end-to-end simulation that would allow the testing of turbo codes in the unique AEHF context. The APL studies produced the first known results relating to the performance of turbo codes in jamming environments[11]—results that were essential to the decision to use these codes in a high-assurance communications system. APL also provided the first published results on channel estimation errors in turbo codes.[12]

The simulation studies were followed by implementation of a prototype. Through both IR&D and direct sponsor support, a hardware test bed was developed[13] for turbo codes based on digital signal processor technology in a configuration called a "software radio." In addition to the turbo encoder and decoder, the radio required a complete set of software modules for a communications transmitter and receiver for data generation, modulation, carrier recovery/synchronization, symbol synchronization, and detection/frame synchronization. Laboratory testing of the turbo-code radio validated the simulation results, and successful transmission and reception of turbo-coded data over an operational satellite[14] (by interfacing the test bed radio to UHF satellite transceivers) provided confirmation of implementation feasibility and the achievement of significant performance gains.

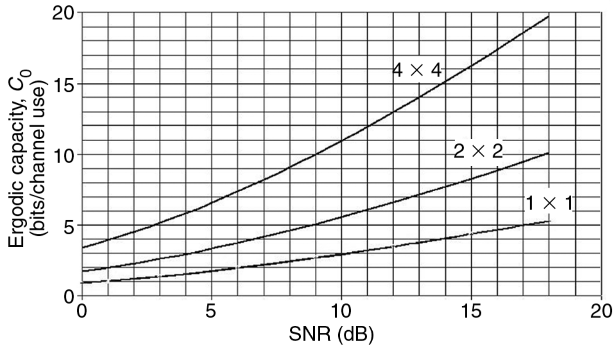

Figure 5. Comparison of the ergodic capacities of three multiple-input multiple-output (MIMO) systems demonstrating the large potential increase in throughput via MIMO techniques.

MIMO Techniques and Space-Time Codes

In wireless RF channels, the performance of a given radio link is typically limited by Rayleigh fading. The loss in signal amplitude (fading) results from the coherent combination of unresolved multipath reflections of the RF signal as it is scattered by the environment. Performance in Rayleigh fading is improved through the use of diversity techniques. In conventional wireless systems, diversity might be provided through multiple receive antennas whose outputs are combined prior to symbol detection. With one receive antenna, as the signal-to-noise ratio (SNR) increases, the bit error rate (BER) typically improves as 1/SNR. With two receive antennas, the BER improves as $(1/\mathrm{SNR})^2$. In general, with L-level diversity, the BER improves as $(1/\mathrm{SNR})^L$.

Recently, researchers discovered[15,16] that when multiple antennas are used at both the transmitter and the receiver, the ergodic capacity of the fading wireless channel (i.e., the maximum information rate that can be reliably supported) far exceeds expectations based on conventional systems. In particular, for an $M \times L$ multiple-input multiple-output (MIMO) system (employing M transmit antennas and L receive antennas) over the wireless Rayleigh fading channel with AWGN, the ergodic capacity $C_0(\mathrm{SNR})$ increases linearly with the minimum of M and L when SNR is sufficiently high. This dramatic increase in potential system throughput is evident in the capacity plots in Fig. 5.

At APL, the effect of partial-band noise jamming on the capacity of frequency-hopped MIMO systems has also been studied under IR&D funding. For a stochastic model of the partial-band noise jammer, one can show[17] that the ergodic capacity is given by the formula

$$C(\mathrm{SNR}, \mathrm{JNR}_0, \rho) = \rho C_0(\delta\,\mathrm{SNR}) + (1-\rho) C_0(\mathrm{SNR}),$$

where JNR_0 is the jammer-power-to-noise-power ratio when the jammer operates in broadband mode (spreading power across all channels to simultaneously jam all hops); ρ denotes the jammer occupancy; and δ represents the loss due to noise jamming on a jammed hop. Note that as the jammer focuses more of its power into fewer jammed channels (i.e., as the jammer occupancy ρ decreases), the loss on that hop caused by jamming increases (smaller fractional value of δ). Numerical evaluations[17] of ergodic capacity as a function of jammer occupancy show that, with the proper design of channel codes, MIMO systems are inherently robust under this type of interference.

For MIMO systems, the channel code should take into account not only the transmission across multiple channel uses (time dimension), as in conventional systems, but also the simultaneous transmission across multiple transmit antennas (space dimension). Such channel codes are commonly referred to as space-time codes.[18–20] Space-time codes achieve levels of diversity that depend on the rank properties of the modulated code words as $M \times L$ complex matrices. The maximum information transmission rate and maximum diversity level of a space-time code are characteristics that must be traded off in the design.

APL is studying the problem of designing space-time codes that achieve the rate-diversity trade-off under a National Science Foundation grant. Recent results[21,22] have provided a unified algebraic design for families of space-time codes that are optimal with respect to the rate-diversity trade-off for commonly used modulation schemes such as $2^K - \mathrm{PSK}$, $2^{2K} - \mathrm{QAM}$, and $\mathrm{AM} - \mathrm{PSK}$ (multiple rings of $2^K - \mathrm{PSK}$). Performance and implementation considerations associated with these constructions are the subject of ongoing research and potential technology transfer.

Adaptive Spectrum Use

Opportunistic access and secondary allocation of spectrum are important research areas for future commercial and military systems. Current policy assigning spectral access to users in a static manner is beneficial in avoiding user conflicts and potential interference, but the demand for spectrum is not uniform across time, space, and frequency owing to population densities and user schedules, so static allocations are not efficient with respect to overall spectrum utilization.

The Federal Communications Commission and the Defense Advanced Research Projects Agency Advanced Technology Office's neXt Generation (XG) Program are investigating opportunistic use of spectrum, whereby users access spectrum based on its availability.[23,24] Such access may necessitate changes to regulatory policies governing access to the RF spectrum. Alternatively, new methods could be used for secondary access within a fixed portion of spectrum. Opportunistic access would open spectrum that is sparsely used (temporally and spatially) to users (military or commercial) who otherwise would be confined to inadequate frequency bands. An XG-enabled radio would sense and characterize spectral activity, identify spectral opportunities for use, and coordinate access, with the goal of not interfering with primary non-XG users.

Opportunistic use of spectrum introduces challenges. If it is implemented as a purely random-access technique, its efficiency will be bounded, as in the case of ALOHA protocols, due to collisions among uncoordinated users attempting to transmit simultaneously. If coordinated access is desired, then control channels are required to convey the overhead information about spectrum availability and access. And if primary users with dynamic spatial and temporal signal characteristics are present, the role of the secondary emitter is complicated by the need to avoid interfering with those users.[25] Thus, packing secondary signals into the spectrum becomes more challenging as use increases.

At APL, an experimental media access control (MAC) protocol has been developed that uses spectrum data from cooperative, spatially separated sensors to identify spectral opportunities and to allocate them for use by the physical layer. Prototype sensor suites have been developed for measuring spectrum use in the 30- to 3000-MHz range. Each suite includes two antennas (one dual-frequency omnidirectional discone and one directional Yagi), filters, amplifiers, downconverters, analog-to-digital converters, storage devices, and timing devices. Data are collected on each channel according to a pre-arranged schedule shared by the spatially distributed sensors. Downconverters are tuned according to the schedule to cover desired bands, allowing any 20-MHz band between 20 and 3000 MHz to be selected.

The APL test bed shown in Fig. 6 has measured spectral use in a number of military exercises to experimentally investigate the dynamic spectral MAC concept. Recent investigations have looked at the 2442- to 2462-MHz band, covering portions of the IEEE 802.11b channels 8 and 11. A representative XG stack, developed

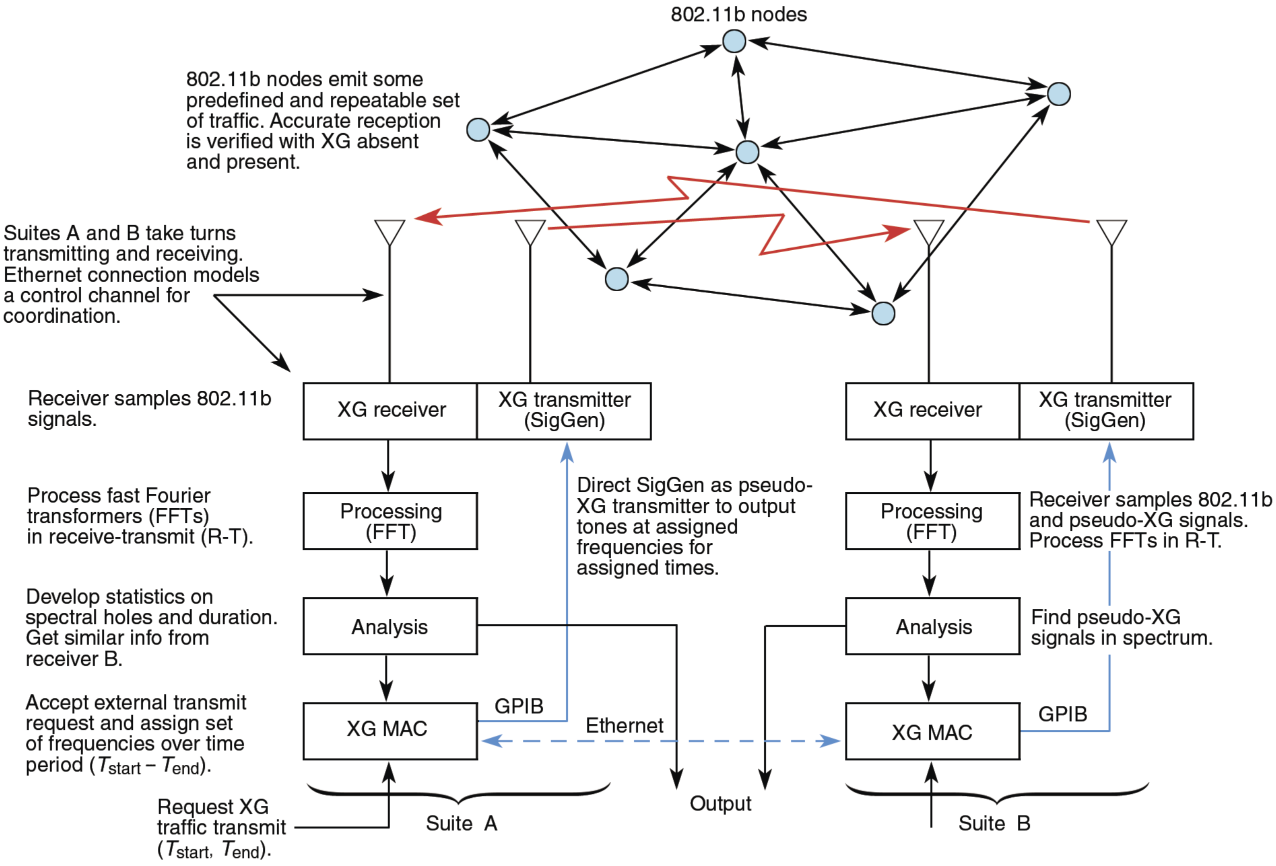

Figure 6. Experimental spectrum-sharing test bed.

by APL, acted as the secondary user, allowing exploration of the relationship between secondary user loading and interference to the primary user.

Cross-Layer Design

The IEEE 802.11 MAC layer provides the basis for all IEEE 802.11 WLAN implementations, including 802.11a, 802.11b, and 802.11g. However, this MAC design is highly inefficient and introduces significant overhead, especially in the case of highly variable network topologies, traffic conditions, and channel conditions. Such inefficiencies are well characterized and documented in the literature. Mitigation methods are documented as well, although most papers have discussed singular, isolated methods of mitigating MAC inefficiency based on some underlying assumption about the network (e.g., number of nodes, relative position of nodes, channel conditions, or traffic characteristics).

APL has developed a concept known as the Network Efficiency Enhancement Device (NEED), which uses multiple methods in tandem to reduce MAC inefficiency and increase throughput for IEEE 802.11–based networks. In this concept (Fig. 7), the 802.11 MAC is enhanced to meet the communications needs of its host military platform through the use of a new traffic scheduler/queuing mechanism and an adaptive MAC controller making use of physical layer information. The traffic scheduler/queuing mechanism performs data packet scheduling to support QoS concepts and shape the traffic offered to the radio to optimize network performance. The adaptive MAC controller configures the various parameters that govern MAC behavior on the basis of incoming traffic characteristics, channel conditions, and the perceived network topology. This functionality, while drawn external to the radio in Fig. 7, could be integrated into the MAC design itself, depending on the degree of COTS reuse that is desired.

The NEED concept is a specific example of adaptive techniques that employ information across layers in the Open System Interconnection (OSI) network model to optimize system performance. Such cross-layer design is an active area of ongoing research.[26,27]

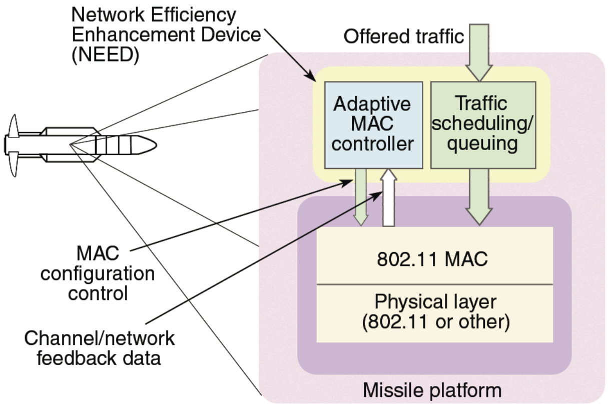

Figure 7. Enhanced 802.11 MAC using cross-layer design.

To provide a systematic and unifying approach to cross-layer design, APL is investigating a generic framework[28] for cross-layer design and adaptation based on formalizing interfaces between the OSI layers. This framework is illustrated in Fig. 8. Conceptually, the standardized interfaces capture the essential performance requirements that the OSI network layers must satisfy to meet user needs while hiding information about the specific details of the protocols implementing that functionality. Success in developing these interfaces, with sufficient generality and in an implementation-friendly manner, would enable the development of protocols that are tailored to a given application and network environment, yet are still interchangeable with similarly designed protocols. Then, an intelligent network—able to determine its current operating environment and evaluate the efficacy of various protocol options for that environment—could swap layer-specific protocols throughout the OSI stack to optimize system performance on the basis of the prevailing environment and the mission needs. Such a network would realize the military's ultimate vision of network-centric operations.

CONCLUSION

Through sponsored systems engineering and development work as well as IR&D efforts, APL continues to respond to the challenges facing military communication systems. The importance of such work will only grow over time as the military develops the GIG and evolves toward its vision of network-centric operations and warfare.

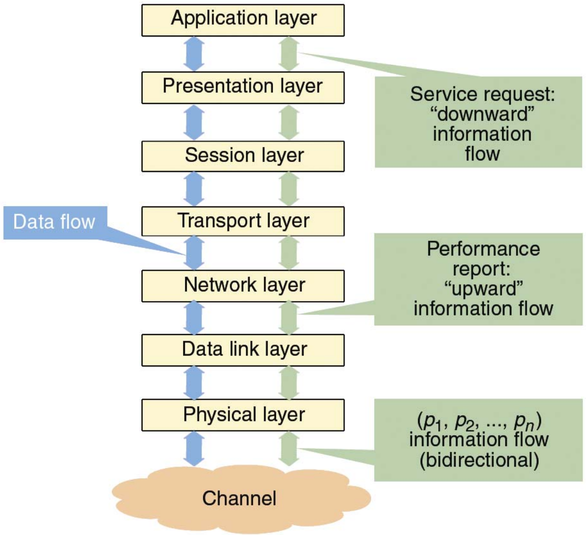

Figure 8. Cross-layer design paradigm based on OSI layers with standardized interfaces

REFERENCES

[1] *Military Operations in Urbanized Terrain Focus Area Collaborative Team (MOUT FACT)*, U.S. Army Modeling and Simulation Office, https://www.moutfact.army.mil.

[2] Andrusenko, J., and Miller, R. L., “Military Operations in Urban Terrain: Tactical Communications and Methods for Prediction of RF Propagation Effects,” in *Proc. National Forum on Weapon Systems Effectiveness*, Seal Beach, CA (Nov 2003).

[3] Williamson, J. (ed.), *Jane’s Military Communications, 2003–2004*, 24th Ed., Jane’s Information Group (2003).

[4] Hashemi, H., “The Indoor Radio Propagation Channel,” in *Proc. IEEE* **81**, 943–963 (Jul 1993).

[5] Rappaport, T. S., *Wireless Communications: Principles and Practice (2nd Ed.)*, Prentice Hall PTR, Upper Saddle River, NJ (2001).

[6] Kasch, W., and Burbank, J., “The Application of Commercial WLAN Technologies for Military Operations,” in *Proc. 2004 MPRG/Virginia Tech Symp. on Wireless Personal Communications*, Blacksburg, VA (2004).

[7] Burbank, J., and Kasch, W., “COTS Communications Technologies for DoD Applications: Challenges and Limitations,” in *MILCOM 2004*, Monterey, CA, 31 Oct–3 Nov 2004 (in press).

[8] Kasch, W., Burbank, J., and Andrusenko, J., “Physical Layer Performance of the IEEE 802.11b WLAN Standard in Outdoor Applications: A Case Study in Yuma, AZ,” in *Proc. 2002 MPRG/Virginia Tech Symp. on Wireless Personal Communications*, Blacksburg, VA (2002).

[9] Berrou, C., and Glavieux, A., “Near Optimum Error Correcting Coding and Decoding: Turbo-Codes,” *IEEE Trans. Comm.* **44**(10), 1261–1271 (Oct 1996).

[10] Jordan, M. A., *Turbo Code Applicability to EHF Satellite Communications*, VS-97-014, JHU/APL, Laurel, MD (Jun 1997).

[11] Jordan, M. A., “Turbo Code Performance in Partial-Band Jamming,” in *MILCOM 1998 Conf. Proc.* **3**, pp. 982–986 (Oct 1998).

[12] Jordan, M. A., and Nichols, R. A., “The Effects of Channel Characteristics on Turbo Code Performance,” in *MILCOM 1996 Conf. Proc.* **1**, pp. 21–24 (Oct 1996).

[13] Jordan, M. A., “Turbo Code Implementation and Performance in a Software Radio,” in *MILCOM 1999 Conf. Proc.* **1**, pp. 525–529 (Oct–Nov 1999).

[14] Jordan, M. A., and Merheb, N. M., “Turbo Coded Radio Performance over a UHF Satellite Channel,” in *MILCOM 2002 Conf. Proc.* **2**, pp. 1335–1339 (Oct 2002).

[15] Telatar, I. E., “Capacity of Multi-Antenna Gaussian Channels,” *Eur. Trans. Telecomm.* **6**, 585–595 (Nov–Dec 1999).

[16] Foschini, G. J., and Gans, M. J., “On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas,” *Wireless Personal Commun.* **6**(3), 311–335 (1998).

[17] Hammons, A. R. Jr., “Effects of Partial-Band Jamming on Space-Time Coded Systems,” in *MILCOM 2004 Conf. Proc.*, 31 Oct–3 Nov 2004 (in press).

[18] Tarokh, V., Seshadri, N., and Calderbank, A. R., “Space–Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction,” *IEEE Trans. Information Theory* **44**, 744–765 (Mar 1998).

[19] Hammons, A. R. Jr., and El Gamal, H., “On the Theory of Space-Time Codes for PSK Modulation,” *IEEE Trans. Information Theory* **46**(2), 524–542 (Mar 2000).

[20] El Gamal, H., and Hammons, A. R. Jr., “A New Approach to Layered Space-Time Coding and Signal Processing,” *IEEE Trans. Information Theory* **47**(6), 2321–2334 (Sep 2001).

[21] Hammons, A. R. Jr., “New AM-PSK Space-Time Codes That Achieve the Rate-Diversity Trade-off,” in *Int. Symp. on Information Theory and Applications (ISITA) 2004*, Parma, Italy, Oct 2004 (in press).

[22] Hammons, A. R. Jr., “On Space-Time Codes and Constellation Labeling,” in *2004 IEEE Information Theory Workshop*, San Antonio, TX, Oct 2004 (in press).

[23] The XG Working Group, *The XG Vision, Request for Comments, Version 2.0*, Defense Advanced Research Projects Agency Advanced Technology Office, http://www.darpa.mil/ato/programs/XG/rfcs.htm.

[24] The XG Working Group, *The XG Architectural Framework, Request for Comments, Version 1.0*, Defense Advanced Research Projects Agency Advanced Technology Office, http://www.darpa.mil/ato/programs/XG/rfcs.htm.

[25] *Principles for Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets*, Policy Statement FCC 00-401, Federal Communications Commission (1 Dec 2000).

[26] Berezdivin, R., Breinig, R., and Topp, R., “Next-Generation Wireless Communications Concepts and Technologies,” *IEEE Commun. Mag.* **40**(3), 108–116 (Mar 2002).

[27] Goldsmith, A., and Wicker, S., “Design Challenges for Energy-Constrained Ad Hoc Wireless Networks,” *IEEE Wireless Commun.* **9**(4), 8–27 (Aug 2002).

[28] Burbank, J. L., Kasch, W. T., Conklin, R. E., and Nichols, R. A., “Cross-Layer Interactions: A Framework for Adaptable Communications,” in *Proc., 2004 MPRG/Virginia Tech Symp. Wireless Personal Communications*, Blacksburg, VA (June 2004).

ACKNOWLEDGMENTS: The authors thank R. A. Nichols for suggesting this article and for his encouragement in the writing of it. This material is based in part on work supported by the National Science Foundation under Grant No. CCR-0325781.

THE AUTHORS

The authors are all members of the Power Projection Systems Department’s Communication Systems and Network Engineering Group. **A. Roger Hammons Jr.** is the Assistant Group Supervisor and an internationally recognized researcher in the area of channel coding. Dr. Hammon’s recent work on space-time codes is supported by IR&D and a National Science Foundation grant. **Jack L. Burbank** is Supervisor of the Theory and Analysis Section. His research interests include wireless communications networks and the application of commercial technologies to military systems. **Steven D. Jones** is a member of the Principal Professional Staff and the Chief Scientist of the group. He is the Lead Engineer for several military communications programs with extensive experience involving architecture, development, analysis, simulation, and testing. **Ross E. Conklin** is a member of the Senior Professional Staff in the Theory and Analysis Section. His research interests include coding, modulation, and adaptive cross-layer design of communications systems. **Naim M. Merheb** is a member of the Associate Professional Staff in the Large-Scale Systems Development Section. His research and development interests include satellite communications. **Michael A. Jordan** is a member of the Principal Professional Staff in the RF Engineering Section, where he provides communications analysis support for a variety of military satellite programs. His research interests include turbo codes and iterative methods. **William T. Kasch** is a member of the Associate Professional Staff in the Theory and Analysis Section. He works on a variety of


A. Roger Hammons Jr.


Jack L. Burbank

(Continued)

wireless communications projects involving hardware, software, and simulation. **Jerry R. Hampton** is the Assistant Supervisor of the Theory and Analysis Section. His research interests include spread spectrum communications, jamming and intercept analysis, satellite communications, and RF propagation. **Julia Andrusenko** is a member of the Associate Professional Staff in the Theory and Analysis Section. Her recent work has focused on military operations in urbanized terrain and military satellite communications. The authors can be contacted through Roger Hammons. His e-mail address is roger.hammons@jhuapl.edu.


Steven D. Jones


Naim M. Merheb


Ross E. Conklin


Michael A. Jordan


William T. Kasch


Jerry R. Hampton


Julia Andrusenko