Airborne Network Evaluation: Challenges and High Fidelity Emulation Solution

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ABSTRACT

The future AN is envisioned as an IP-based hierarchical network with heterogeneous nodes and waveforms. Due to its highly dynamic nature and bandwidth constraints, new AN technologies are needed to provide reliable network operations with similar levels of mission support as in terrestrial networks. This article first identifies challenges in designing and evaluating AN technologies and then describes an ongoing effort to develop a realistic wireless testing and performance evaluation platform for ANs. A set of use cases are presented to illustrate how high fidelity emulation can be used to evaluate new architectures and protocols in AN environments.

INTRODUCTION

Net-centric warfare demands effective linking or networking of various network assets that are geographically or hierarchically dispersed, operating with various protocols, communication links, and waveforms (e.g., RF, optical, and SATCOM), organized in different topologies. The networking of knowledgeable network assets further facilitates information sharing to ensure shared situational awareness and mission success. The former Air Force Chief of Staff, General John Jumper, initialized the effort of airborne networks (ANs) with seamless integration of an IP-based network in the sky into the global information grid (GIG). As illustrated in Fig. 1, ANs will provide such an enabling networking infrastructure, which consists of IP-based airborne nodes that provide interconnectivity among terrestrial networks, space networks, maritime networks, and various other types of networks through backbone in the sky as part of the GIG. One of the main goals of ANs is to reduce the sensor-to-shooter timeline by combining data from disparate sensors, air platforms, and ground stations. Future AN technologies will be capable of supporting diverse heterogeneous networks (subnets) operating with various protocols and communication links, and forming different topologies. The constellation of intelligence, surveillance, and reconnaissance (ISR), command and control (C2), and targeting networks are examples of subnet technologies.

Current military networks provide only their own mission-specific implementations, operate at different frequency bands, use different waveforms (e.g., Link 16, tactical targeting network technology [TTNT], common data ling [CDL], multifunction/situation advanced data link [MADL/SADL], optical/laser, and SATCOM), and provide limited interoperability and autonomous routing capability. In order to enable the vision of networked information exchange across all these subnets, an autonomous end-to-end networking solution needs to be developed. Toward this goal, significant research efforts have been made on designing efficient networking technologies to fulfill the stringent requirements of ANs, such as high network dynamics, bandwidth efficiency, security, and robustness.

The process of testing and evaluating various AN technologies in a realistic way remains a big challenge in AN research and development. In other words, once the necessary networking technologies are identified and the development phase starts, they need to be thoroughly tested and evaluated to justify their feasibility and performance. *Simulations* are typically simplistic and cannot fully capture physical channel effects in the AN environment. On the other hand, static *testbeds* in a laboratory environment cannot reliably represent network dynamics, whereas *field tests* with real hardware in relevant environments are costly to execute. This article describes test and evaluation (T&E) challenges, and introduces a realistic wireless *network emulation* solution to reliably test and evaluate innovative technologies as well as modifications to existing protocols under realistic AN scenarios. Diverse use cases are presented to show how one can use a high fidelity wireless channel emulator to reduce the cost and increase the speed of design, prototyping, and deployment of AN technologies.

The rest of the article is organized as follows. The next section identifies the design and evaluation challenges in ANs. After that, we summarize the state of the art of AN performance evalua-

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tion approaches. Then the unique capability to emulate airborne communication channel for realistic performance evaluation and verification through several use cases is presented. Finally, we present our conclusion.

Airborne Network Design and Evaluation Challenges

To support heterogeneous network integration and autonomous end-to-end networking in ANs, we need to overcome many challenges [1–3]. This section summarizes two categories of challenges: design challenges and evaluation challenges.

Design Challenges

The design challenges highlight issues and potential complications of AN design and development due to its inherent unique characteristics. We first introduced the potential airborne platform architecture described in the Joint Airborne Network Service Suite (JANSS) standard definition document [4, 5]. The JANSS document describes the concept, capabilities, functions, and standards of JANSS. The JANSS standard is a fundamental building block of the future AN infrastructure. It will provide a common path toward IP network evolution and implementation, and allow air and maritime platforms to interoperate with each other, with other edge tactical networks, and with ISR networks that are equipped with transparent IP connectivity.

The JANSS document defines the airborne platform configuration in terms of the necessary functional blocks (e.g., name service, address service, service discovery, mobility management, security service, and network management). As shown in Fig. 2, a number of local area networks (LANs) could be supported on the airborne platform. These LANs access the network through the platform's AN router, which may have multiple RF paths via IP-capable radios. As illustrated in Fig. 2, these IP radios would have their own *mobile network routers*, which implement their respective mobile routing protocols, as part of their system. Since multiple levels of security should be supported, access to information and services should be based on different sensitivity level classifications, and specific policies, procedures, and requirements to ensure that the information will be mutually invisible among different levels/classifications/compartments.

- The networking mechanisms need to be impervious to network dynamics in ANs, and this poses a great challenge for protocol and service design (e.g., robust IP address assignment). Due to the highly dynamic nature of ANs, infrastructure-based network service protocols, such as Dynamic Host Configuration Protocol (DHCP) and Domain Name System (DNS), are not readily applicable, since they are specifically designed for a stable, always connected, and error-free network environment.
- The network integration and auto-configuration approach should be able to operate autonomously without connectivity to external servers. In such a dynamic mobile network, autonomous and auto-configurable functionalities are needed to perform network services.
- The security approach needs to be capable of operating autonomously without connectivity to external infrastructure. In such a mobile network, the mobile platform acts not only as a host, but also as a router or server for other mobile platforms. Some platforms may even act as a gateway to a subnet of platforms. Whenever any node loses its connection to the ground servers or external networks, the network security services are required to support operation in an autonomous and reconfigurable mode.
- ANs need to meet stringent application requirements on data delivery. A set of applications have been enabled in ANs, and these applications have high real-time and reliability requirements. In particular, a longer end-to-end delay may render surveillance information meaningless, and the potential loss of messages, for example, due to security attacks, may affect mission-critical decisions.
- Due to the inherent limit on interface and communication links, bandwidth efficiency is a critical factor. The communication link in ANs is capac-

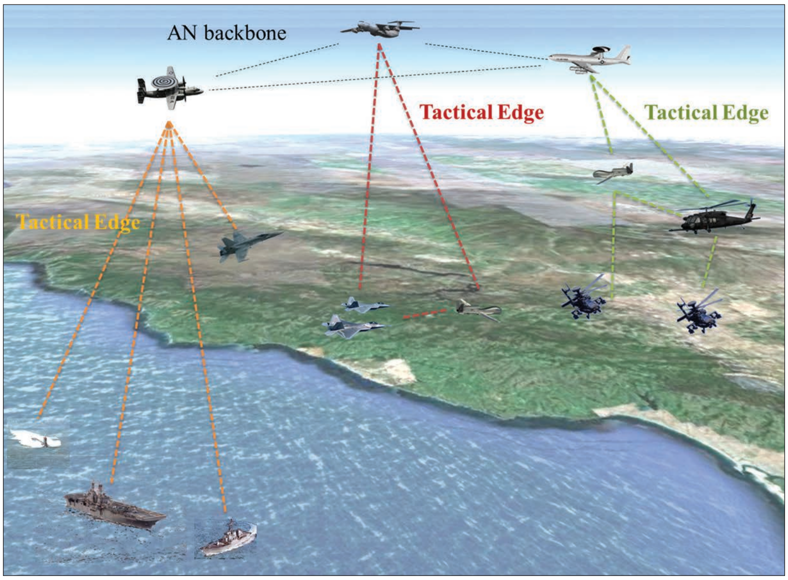

Figure 1. Airborne network architecture.

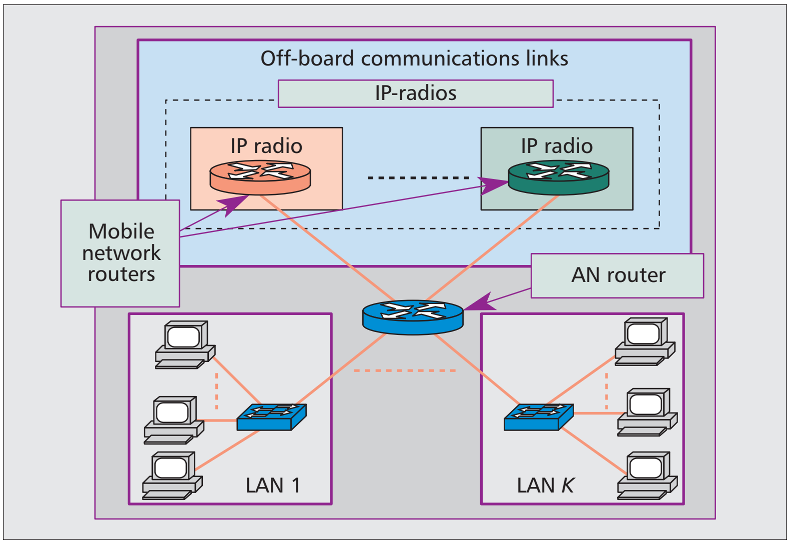

Figure 2. Airborne platform architecture [4].

RFnest is an FPGA-based network channel emulator, which allows all of the channels in a full mesh network to be emulated in real time, with all communications experiencing a realistic channel impulse response and correct interference.

ity-constrained and subject to significant transmission delays. Any network operation (e.g., integration and security mechanism) that is expensive, cumbersome, prone to human error, and non-scalable is typically not appropriate for large-scale ANs.

- An airborne router should provide the capability to select the appropriate link and interface robustly. The underlying autonomous (re)configuration capability should provide seamless end-to-end communications in dynamic heterogeneous AN environments.

Evaluation Challenges

The evaluation challenges point out requirements and limitations of existing evaluation solutions. AN technologies should be evaluated in highly dynamic and mobile wireless environments for reliable test, measurement, and deployment. The following summarizes evaluation challenges.

- AN field tests are costly and hard to execute. Hence, there is a strong need to develop an initial in-laboratory testing capability that can increase the speed of AN protocol and algorithm design, and reduce the cost of prototyping and deployment. The lack of realistic and cost-efficient testing and performance evaluation capabilities delays the wide application of innovative technologies in ANs.
- Transmission power, modulation, coding, interference, node mobility, and channel conditions all vary over time, and induce significant fluctuations in key quantities such as link capacity and delay. Performance evaluation of ANs is challenging because of the highly dynamic nature of the communication environment, including platform speed, beyond line of sight (BLoS)/directional link, Doppler effects, path loss, and delay.
- To provide realistic and practical test and performance evaluation results, and derive guidelines for future research and development, AN evaluation methods should be repeatable with high fidelity such that different sets of parameters can be tested over the same environments and scenarios. This way, a fair comparison of different AN technologies can be achieved with trustworthy results and assessment in a repeatable environment.
- Current testbeds are typically limited by stationary topologies of fixed size. More scalable evaluation solutions are needed in a highly dynamic and mobile wireless environment, as AN architecture grows and expands to space and terrestrial networks.

Current Airborne Network Evaluation Approaches

There are several approaches to test algorithms/protocols and evaluate their performance within AN scenarios. These approaches can be classified into three main categories: simulators, testbeds, and field (flight) tests.

Simulators are mainly implemented in software with OSI layer model implementation. Network Simulator (NS)-2/3, QualNet®, and OPNET belong to this category. Simulators are limited to simple and unrealistic physical (PHY) and medium access control (MAC) models. Although more complete and complex external PHY models (e.g., Matlab Simulink) can be integrated, computation overhead/delay is typically extensive, and such solutions do not scale well with network size. In addition, the Matlab models should be thoroughly verified to confirm that they are realistic enough, and can capture some nonlinear and unexpected characteristics of both wireless channels and radio transceiver systems.

The alternative is testbed experimentation with hardware. For example, the CORNET testbed from Virginia Tech provides 48 USRP-2 platforms in a four-story building. The RoofNet testbed deploys 40 nodes over the city of Cambridge, Massachusetts. Similarly, the CitiSense testbed developed by the University of California, San Diego utilizes several stationary nodes and mobile platforms. Finally, the ORBIT testbed contains 20 × 20 802.11 nodes, USRPs, and RF interferers. However, the use of testbeds is costly, and its accessibility, scalability, and repeatability are typically limited. Also, most testbeds are set up in a laboratory environment with static 2D topologies and cannot capture the essence of highly dynamic/mobile AN environments.

Other than the above two types of evaluation approaches, a fair amount of effort has been put into evaluating new technologies with real airborne platforms in field tests (e.g., flight tests). For example, Battlefield Airborne Communications Node Joint Urgent Operational Need (BACN JUON) and Communications AirBorne Layer Expansion Joint Capability Technology Demonstration (CABLE JCTD) deployed several airborne platforms and ground stations to prove the initial AN capability. However, flight tests are very expensive, and require tremendous effort to plan, prepare, and execute.

The limitations of simulators, testbeds, and flight tests can be overcome with *network emulation* solutions. For example, Carnegie Mellon University's field programmable gate array (FPGA)-based wireless channel emulator [6] provides network channel emulation with high fidelity. However, scalability remains limited. There are also commercial channel/network emulators [7, 8], but they cannot represent network interactions beyond point-to-point channels or small number of channels. Recently, FPGA-based channel emulators [9, 10] have been developed. Their fundamental concept is similar to the RFnest™ in that channel effects are manipulated at the digital signal domain. However, detailed designs and their implementation are different from each other. The next section describes a unique wireless channel emulation framework that will be useful for AN technology testing and evaluation.

High Fidelity Airborne Network Emulation Testbed

Radio Frequency Network Emulation and Simulation Tool: RFnest

To bridge the gap between high fidelity of a hardware-based network emulator and scalability of a software-based network emulator, Intelligent Automation, Inc., developed a wire-

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less network emulator, RFnest [11], and ran a large number of tests and experiments with it for ANs. RFnest is an FPGA-based network channel emulator that allows all of the channels in a full mesh network to be emulated in real time, with all communications experiencing a realistic channel impulse response and correct interference. RFnest consists of three modular components:

- FPGA-based emulation hardware with RF front-ends that allows real radios to send their RF signal over an emulated channel without any modification on the radio. The FPGA digitally modifies the signals based on channel impulse response, Doppler, airframe characteristics, propagation delay, and channel models.
- Modeling of time-varying channel impulse response with channel properties based on mobility patterns defined in a scripted or interactive graphical user interface (GUI) environment feeds computation output into the FPGA. This feature also enables feeding geographical information into channel emulation to provide a more realistic testing and evaluation environment that is very close to the actual channel condition.
- Integration with network simulators and monitoring functionality allows the user to instantiate, manage, and monitor real and virtual network nodes within the scenario. This capability can be achieved by using Boeing's Common Open Research Emulator (CORE) [12] and Extendable Mobile Ad Hoc Network Emulator (EMANE) [13] with additional queueing and channel switching mechanisms. RFnest is the first network emulator that allows virtual simulated nodes and real RF nodes to interact with a synchronized wireless channel effect. This can be achieved by letting the real RF nodes receive the signals sent by the virtual simulated nodes on their real radios and vice versa through RFnest. This innovative feature enables both high fidelity and scalable network simulation and emulation with the same set of controlled and repeatable conditions.

Table 1 lists the detailed hardware specification of RFnest, and Fig. 3 shows the actual hardware setup architecture of RFnest.

<table>
<tr><th colspan="2">Model</th><th>Analog</th><th>Digital</th></tr>
<tr><td colspan="2">Frequency band</td><td>0– 4.0 GHz</td><td>20 MHz–6.0 GHz</td></tr>
<tr><td colspan="2">Maximum bandwidth</td><td>Any</td><td>30–200 MHz</td></tr>
<tr><td colspan="2">Nodes</td><td>8</td><td>Up to 24 per module</td></tr>
<tr><td colspan="2">Channels</td><td>28</td><td>Up to 276</td></tr>
<tr><td colspan="2">RF configuration</td><td>SISO, SIMO, MISO, MIMO,MESH</td><td>SISO, SIMO, MISO, MIMO,MESH</td></tr>
<tr><td colspan="2">Dynamic range</td><td>30–40 dB</td><td>60 dB digital
60 dB analog</td></tr>
<tr><td colspan="2">RF output accuracy</td><td>1 dB</td><td>0.5 dB</td></tr>
<tr><td rowspan="6">Channel model</td><td>Freq flat fading</td><td>Yes</td><td>Channel model</td></tr>
<tr><td>Freq selective channel</td><td>No</td><td>Yes</td></tr>
<tr><td>Doppler</td><td>No</td><td>Yes</td></tr>
<tr><td>Maximum delay</td><td>N/A</td><td>500 ms</td></tr>
<tr><td>Number of taps</td><td>N/A</td><td>20</td></tr>
<tr><td>Topologies supported</td><td>Most</td><td>Any</td></tr>
<tr><td colspan="2">Virtual node support</td><td>Yes</td><td>Yes</td></tr>
<tr><td rowspan="2">Interference</td><td>Live RF source</td><td>Yes</td><td>Interference</td></tr>
<tr><td>Digitally injected</td><td>No</td><td>Yes</td></tr>
</table>

Table 1. RFnest hardware specifications.

AN Emulation Use Cases

This section identifies four use cases to illustrate how RFnest supports the emulation needs to evaluate new architectures and protocol designs under realistic AN environments.

Model Validation — Conventional methods to evaluate wireless channel model performance are based on simulation, and comparison between simulated results and field test measurements. Such a process is usually cumbersome, expensive, and unrepeatable. However, RFnest can digitally create scenarios for real radios identical to those used in a simulation. The results from the radios can then be compared to those obtained from the models. By doing so, evaluation of wireless channel performance becomes more reliable and repeatable. The following describes an effort to model a wireless airborne channel and the use of RFnest to evaluate the channel model.

Accurate Bidirectional Wireless Channel Model — The extremely large scale and complexity of terrain scenes pose a unique challenge in channel modeling of aeronautic telemetry. This becomes even more difficult if severe multipath and fading are present due to scattering and attenuation of ground, terrain objects, and precipitation. Such features are critical in more sophisticated test scenarios involving low-altitude unmanned air vehicles and helicopters tested over water at high sea states, in hilly terrain, or even over an urban environment. This channel impulse response can then be provided to RFnest, which allows a user to predict the link performance using real radios connected to RFnest for further performance evaluation and comparison.

Repeatable and Affordable Field Test Environment Generation — It is quite common to observe a problem (e.g., low performance) or misbehavior (e.g., unexpected performance) of a protocol/algorithm during a field test. After any modification is introduced, its performance is evaluated, typically through simulations with replicated scenarios, hoping the previous problem is fixed. However, better simulation results do not always guarantee that the problem will

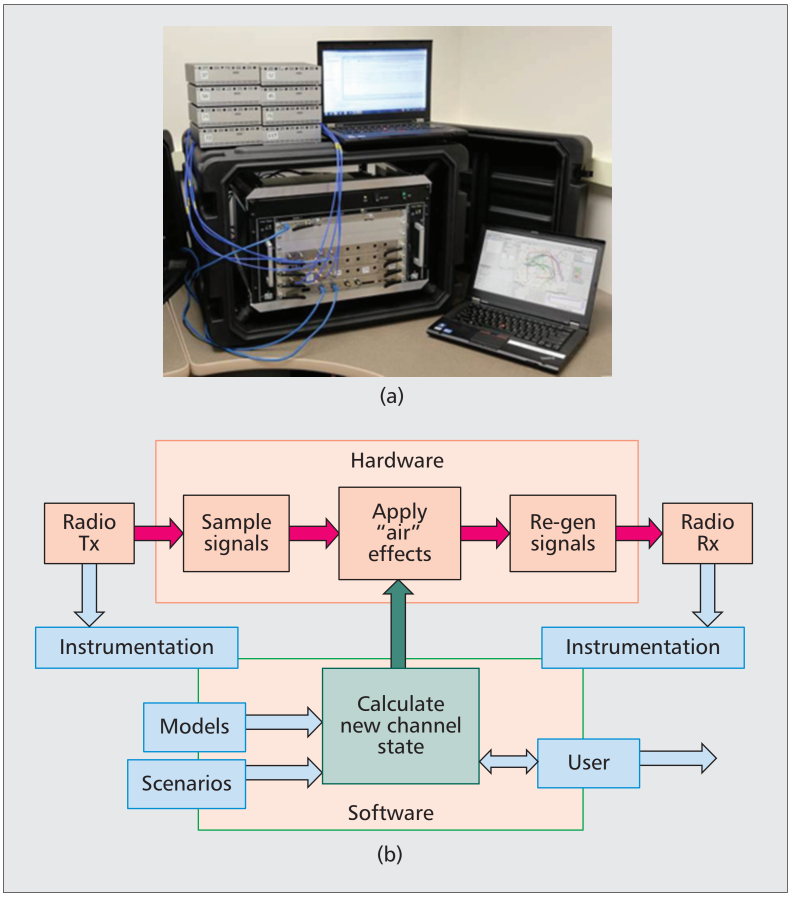

Figure 3. RFnest: a) RFnest D500 hardware setup; b) notional architecture.

not occur again in another field test because of limitations posed by unrealistic simulation models. RFnest can reproduce a high fidelity testing environment, where a modified protocol can be re-evaluated with the same radio device and RF condition. The following illustrates challenges in AN protocol design, and how RFnest can help evaluate new protocols and algorithm design at various OSI layers.

Robust Network Service Framework — As ANs must be capable of self-forming and self-adapting with nodes dynamically joining or leaving the existing network, performing network services over an AN is a challenging task. Several applications require proper network service support on the airborne platforms including auto-configurable addressing, human usable naming, time synchronization, and security support. New technologies and protocols can be tested over RFnest [14] with a repeatable test environment. Several mobility scenarios and multiple applications can run across multiple subnets through mobile nodes and an airborne backbone network. The high fidelity wireless evaluation efforts will help engineers confirm the feasibility of new technologies and protocols running in dynamic environments.

Hybrid Airborne Router — It is quite common for an airborne platform to have multiple interfaces with different waveforms running on different routing mechanisms. Since each waveform has unique characteristics and capabilities, it would be beneficial to share link information (e.g., topology, neighbor information, and link/PHY parameters) among different interfaces for better decision support of when and which interface to choose in order to meet the broad spectrum of mission requirements. RFnest was easily configured to emulate multi-interface environments and highly dynamic platform mobility (e.g., subnet merge/split and node join/leave events). It also provided the necessary RF conditions to test interface switching mechanisms and other functionalities.

Hyperspeed Mobility Management — A hyperspeed node is capable of traveling at Mach 3 or higher speed, and thus the duration of contact between neighboring airborne nodes may be extremely short (e.g., a few seconds). Such hyperspeed mobility combined with complex operational environments may cause the existing mobile ad hoc routing protocols to fail in providing secure and reliable connectivity. To deal with such limitations, it is highly desired to develop hyperspeed mobile and security capabilities suitable for a hyperspeed airborne platform. Once such capabilities are designed and developed, it is quite challenging to evaluate its performance under realistic operational environments due to hyperspeed mobility and its corresponding channel effects. RFnest provided the capability to create a scenario with configurable flight paths and realistic wireless channel/network effects (e.g., hyperspeed mobility, Doppler effect, propagation delay). This ensures reproducible evaluation environments to make mobility and security solutions more practical and effective.

Autonomous Routing for UASs — The increasing availability of small unmanned aerial systems (SUASs) leads to the possibility of forming temporary mission-centric networks using multiple SUASs. Such networks have the potential to increase the range of SUAS operation, provide improvements for communication capabilities, and ease operational constraints imposed by communication needs. There are several major problems faced in achieving this vision, such as the highly dynamic nature of SUAS topologies and limited bandwidth. These combined effects create an environment that is inhospitable for traditional routing approaches. To achieve the vision of SUAS-based networks, new routing approaches must be developed to overcome this highly dynamic nature of SUASs. To evaluate new routing schemes, RFnest provides a highly realistic test environment by using SUAS path planning and geographic/terrain information. This is a key factor because different routing schemes should be compared under the same environment. In particular, RFnest was used to replay real RF channel measurement data to emulate real UAV communication channel effect.

Cross-Layer Protocol Design — Modern PHY layer techniques such as modulation, channel coding, rate adaptation, and diversity techniques make it possible to design a wireless link that can achieve data rates close to the theoretical

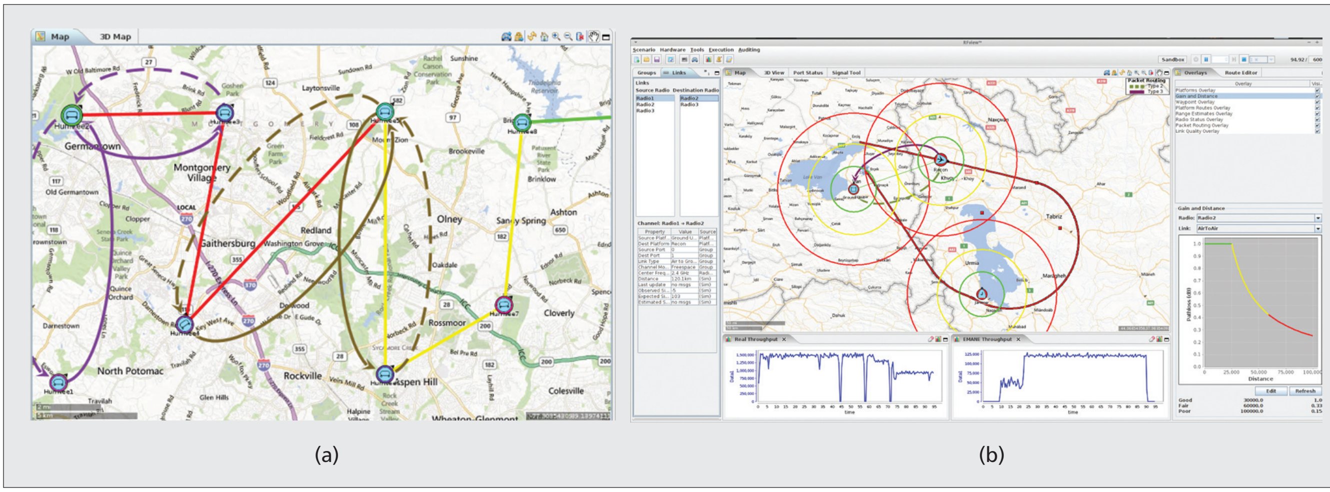

Figure 4. RFnest use cases; a) airborne node path planning with geographical obstacles; b) cognitive radio evaluation in a dynamic wireless environment.

capacity limit for a specific channel condition. Unfortunately, AN communication channel conditions are not stationary, so many capacity-achieving techniques for one channel condition may result in severely degraded rates of others under different channel conditions. To overcome such limitations, a different strategy in PHY layer design is required to make wireless links more reliable. The cross-layer protocol, including MAC and network protocols combined with superposition coding, provides multi-rate transmission and supports different coverage areas based on link information. Similar to the aforementioned projects, RFnest provided realistic airborne channel/network effects (e.g., propagation delay, multipath and Doppler effect, signal attenuation) to test and evaluate a multi-objective superposition coding solution.

Cognitive RF Evaluation — ANs may use cognitive radio capabilities to perceive and learn the wireless environment, and adapt to network dynamics at both the signal and traffic levels. In cognitive radio networks, primary users transmit on dedicated channels, and secondary users sense and opportunistically access primary user channels. To support dynamic spectrum access, different capabilities must be built to support multiple transmission configurations (multiple channels at different frequencies, diverse transmission powers and rates), heterogeneous user classes (primary and secondary users, and jammers/adversaries), and signal-level interactions among users in terms of both spectrum sensing and data transmission. In particular, the manner in which cognitive radio network protocols respond to realistic physical channel effects can be tested over RFnest [15] with controlled RF transmissions by software-defined radios (SDRs). The real value of RFnest lies in enabling the evaluation of reliable signal-level interactions among primary and secondary users by providing the necessary cognitive radio network flexibility to configure diverse transmission parameters, emulate realistic physical channel and topology/mobility effects, and collect reliable performance (e.g., throughput and delay) measurements.

Realistic Jamming and Electronic Warfare Evaluation — Recent tactical operation environments raise the need to consider harsh RF conditions while evaluating and validating new technology and hardware. However, it is not easy to accommodate proper RF interference in field tests and over-the-air evaluation due to government regulation, or run multiple field tests for performance evaluation in different RF conditions. However, RFnest allows any emitters to be simply added without any restrictions (e.g., power level, location, and frequency) since the emitted signal is confined to RF cables. In addition, RFnest can effectively replay recorded channel properties from a field test to produce repeatable evaluation of RF environments. Such capabilities vastly accelerate the electronic warfare (EW) development process by providing in-laboratory evaluation and analysis of an entire EW scenario consisting of existing physical RF devices (e.g., radios, emitters), traditional SDR platforms (e.g., USRP, JTRS), concept devices defined via EW primitives instantiated in the system hardware, and/or known EW threats.

Figure 4 shows snapshots of the RFnest GUI for different use cases. In addition to these use cases, RFnest was used to test and evaluate different wireless/mobile network technologies with direct applications in ANs, including utility-optimal carrier sense multiple access (CSMA), distributed power control, backpressure scheduling and routing, network coding optimization, adaptive service discovery framework for mobile ad hoc network (MANET) environments, and service oriented architecture (SOA) extension for maritime networks. In all these cases, RFnest provided high fidelity and scalability to realistic and repeatable experimentation in highly dynamic mobile wireless environments that can reliably represent AN characteristics.

CONCLUSION

Due to the inherent network dynamics and heterogeneous platforms/waveforms in ANs, innovative technologies and extensions of existing wireless solutions are needed to guarantee reli-

This article has identified challenges in AN design and evaluation, and introduced an efficient and realistic testing and evaluation approach for AN technology.

able end-to-end connectivity. This article has identified challenges in AN design and evaluation, and introduced an efficient and realistic testing and evaluation approach for AN technology. We have presented different AN use cases and discussed the need for high fidelity wireless network emulation of ANs. We have also presented use cases for a high fidelity network emulation solution and pointed out the benefits of cost-efficient, scalable, and highly accurate testing and performance evaluation of new AN technologies.

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JASON LI is currently a vice president and senior director at IAI, where he has been working on research and development programs in the area of networks and cyber security. Over the years he has initiated and worked on numerous R&D programs related to protocol development for satellite networks, airborne networks, realistic and repeatable wireless networks test and evaluation, moving target defense, cyber situational awareness, and ad hoc and sensor networks.