A Description of the August 2006 XG Demonstrations at Fort A.P. Hill

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Abstract-On Aug 15-17, 2006, Shared Spectrum Company (SSC) and the U.S. Department of Defense's Defense Advanced Research Projects Agency (DARPA) demonstrated, for the first time, a six node network of Next Generation (XG) radios capable of using spectrum over a wide range of frequencies on a secondary basis. The cognitive radios making up several formations of XG networks sensed radio signals over 225-600 MHz and adapted frequencies automatically to prevent interference to existing military and civilian radio systems. The XG networks were tested on a military test range (Fort A.P. Hill, Bowling Green, VA) in front of an audience of over one hundred military and government spectrum management agency representatives from the Army, Navy, Air Force, Coast Guard, Joint Spectrum Center, the Federal Communications Commission and the National Telecommunications and Information Administration. This paper describes the XG radio system and test scenarios. A companion paper presents a detailed account of the test results.

Index Terms— ad hoc networks, cognitive radio, distributed frequency sharing, radio spectrum management, software defined radio

I. INTRODUCTION

COGNITIVE radio hit a new milestone in August 2006, as Shared Spectrum Company (SSC) and the U.S. Department of Defense's (DoD) Defense Advanced Research Projects Agency (DARPA) demonstrated mobile adaptive XG technology against military and civilian radios on an army base in front of government participants and witnesses at Fort A.P. Hill, in Bowling Green, Virginia. The tests proved that dynamic spectrum access networks (DySPAN) work and that military frequencies can be accessed automatically and dynamically without interference to other legacy radios using the same frequencies. Our intelligent, adaptive radios used sophisticated algorithms and gaps in frequency and time for sensing the legacy radios and for their own communications.

This paper describes the test conditions and test scripts of this historic demonstration, which proved the feasibility of SSC's and DARPA's frequency sharing concepts. This paper presents the tests that were designed to prove those concepts and what the tests show about the capabilities of XG radios. Other papers presented at this conference by SSC employees will present the comprehensive results of the field tests, describe the sensor technology utilized, and the XG policy control system that has been developed [1], [2], [3].

II. HISTORICAL NATURE OF XG DEMONSTRATIONS

A. Spectrum Depletion

Spectrum managers have long been concerned about spectrum depletion of available spectrum in communities assigned stove-piped frequencies from a larger frequency pool. For example, the Federal Aviation Administration (FAA) has estimated that its VHF spectrum will be exhausted by 2015 due to growth in spectrum usage [4]. The White House has been concerned enough to start a Presidential Spectrum Policy Initiative and create a multi-agency Federal Government Spectrum Task Force [5] to focus on interagency initiatives to use spectrum better and more efficiently. This calls attention to the fact that spectrum is a finite resource of great economic value.

B. Spectrum Usage

National Science Foundation (NSF)-funded spectrum usage measurements [6],[7] have shown that the actual amount of spectrum used, averaged over time, space, and frequency, is about 14%, with about a 2-3% swing depending on the location measured. This is the busy-period percentage during the day, when wireless traffic is at its peak, and is true in the United States' largest cities. This means that spectrum can be re-used in real time if radios were sufficiently nimble and well designed, and if re-use protocols could be developed which could make use of the remaining 86 %.

C. The Rise of SDR and Cognitive Radio

Software defined radio (SDR), which integrates processors into a radio and makes the radio's modulation, coding, framing, and MAC layer functions software programmable, is being integrated into cellular telephones, walkie-talkies, satcom radios and military communications. The falling cost of processors allows radios to be used more flexibly, thus

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increasing usefulness in multiple bands and potentially increasing radio system lifecycles.

Simple cognitive radios exploit the falling cost of geolocation systems such as GPS to make radios aware of their locations and adapt to changes in regulations with geographically defined boundaries. This is especially important in military radios when military frequency managers' Areas of Operational Responsibility (AORs) cross country lines [8]. More advanced cognitive radios are capable of sensing their spectral environment, probing for information and learning from their experiences with complex software algorithms.

D. DARPA XG Radio Program

DARPA, recognizing the convergence of radio technology advances with increased need for better use of spectrum, developed the Next Generation (XG) radio communications program [9], which focused on the transformation of spectrum assignment technology for DoD applications through dynamic spectral use. The burden of sharing spectrum falls on XG radios, which must detect legacy radio systems (who are "primary" users of the frequencies in terms of regulatory priority) and not interfere with them, without *a priori* knowledge of the legacy radio waveform, MAC layer protocol, radio positions, transmit powers, or receiver sensitivities. Since legacy radio systems have primary access rights to the spectrum, many were not designed to cooperate or interoperate with secondary users like the XG radios; hence, these legacy radios are often referred to as "non-cooperative."

While many papers have been written and simulations conducted on the concepts of dynamic frequency access and coexistence of cognitive and non-cooperative nodes, there are no published reports of anyone having successfully demonstrated such capabilities in field tests until now. On August 15 - 17, 2006, SSC and DARPA demonstrated, for the first time, a six-node network of XG radios capable of using spectrum over a wide range of frequencies on a secondary basis. The XG networks sensed radio signals over a wide range of frequencies from 225 to 600 MHz.

SSC and DARPA demonstrated successfully operating XG detection algorithms against fielded DoD military and civilian radio systems in realistic operational scenarios, as well as frequency reassignment, rendezvous, and frequency negotiation among disparate XG networks. XG networks, in a variety of configurations were able to operate with up to six nodes while mobile. Tests were held on a DoD military training test range, Fort A.P. Hill, Bowling Green, Virginia, the same range that is used by a variety of other military radio systems for operational test and evaluation.

Building on previous work, it was demonstrated that Listen-Before-Talk and Look-Through methods would work in multiple-network environments and would allow existing legacy radio networks to operate without interference. A Policy Manager was used to operate in distinct frequency bands under experimental authorizations granted by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) in cooperation with the A.P. Hill frequency manager.

The ability of XG networks to support a variety of traffic loads, ranging from low-bit-rate data up to streaming video was demonstrated. XG's live performance used a mix of preplanned scenarios and unanticipated movements determined by DARPA and neutral observers. The pre-planned scenarios were used to demonstrate the XG cognitive radios operating under a variety of rigorous test conditions. Spontaneously directed movements of XG nodes allowed witnesses to suggest where to move XG nodes. Observers watched real time displays of XG frequency adaptation, XG link performance, and non-interference to legacy radio networks. The result was a clear demonstration that XG radios were working properly. A few times XG networks did not behave as predicted. These showed correctable weaknesses in XG algorithms, which resulted in a list of improvements as a part of DARPA's Technology Maturation program for XG. The fact that these field trials were live and were witnessed by over one hundred U.S. Government and industry representatives permitted SSC and DARPA to receive instant feedback after each demonstration test.

III. THE XG RADIO

A. XG Radio Description

The demonstration version of the XG radio node consisted of four key components, as shown in Fig. 1:

- OFDM modem with IEEE 802.16-2004 based chipset
- Wide-bandwidth energy detector / radiometer
- Wideband, frequency agile transceiver (225-600 MHz)
- General-purpose processor running XG software



Figure 1. XG node block diagram.

B. An XG Node

1) Modem

The 802.16-2004 modem, supplied by Wavesat, Inc., is a high bit rate modem intended to be used in static spectral environments (with dedicated channels) as a wireless local loop modem. Modulation is orthogonal frequency division multiplex (OFDM). The IEEE 802.16d air interface protocol is intended to transport voice as well as data, but has profiles only for particular bands and in fixed network configurations.

The time division multiple access (TDMA) frame structure is variable frame length of between 1 and 20 msec, with distinct uplink and downlink burst time periods within each frame. Each frame has order wire slots which can be used by new network members to request time slots. The frame is very flexible: Uplink and downlink burst time slots depend on traffic loading. Some users will be granted more time for their time slots depending upon the amount of data in their MAC queues (which depends on traffic loading). Time slot management and scheduling is a large part of the complexity of designing with the WiMAX modem. Unfortunately, crucial scheduling and time slot management software was not released with the modem hardware, and the XG development team spent a considerable amount of time creating such software to meet Demonstration 3 objectives. For the sake of simplicity SSC used a fixed 5 msec frame length for all of its tests. Slot assignments were configured manually, depending on the scenario. A 6 node network with one base station was set up to have one downlink slot (base to subscriber) and five uplink slots (subscriber to base). Slot lengths were fixed, which meant that each subscriber had the same constant bit rate capacity available to it, i.e., there was no ability to adapt this XG network to give more capacity for a user who needed it. One of our assignments for follow on XG phases is to make each node have rate-adaptive load-adaptive capacity.

The IF bandwidth is variable, between 1.75 MHz and 10 MHz. IF frequency is 13.5 MHz. Baseband interface is Ethernet. The rate adaptive nature of the modem is one of the primary reasons it was selected for DARPA XG.

The WiMAX modem's features for Demo 3 do not include the following:

- Ad-hoc networking
- Ability to do automated network establishment
- Ability to do automated network joins
- Mobility features and robustness to Doppler shift inherent in mobile nodes

At time of development, these features were not available by Wavesat, and were left to individual developers to create. This was a key development hurdle for SSC software developers. These features will be developed in future XG phases.

The lack of ad-hoc networking support meant that when more than two nodes were in a network, the network was point to multipoint, and not a true ad-hoc network.

OFDM subcarrier modulation types include BPSK, QPSK, 16-QAM, and 64-QAM. BPSK is used for beacons, and cannot be used for data transport. QPSK is used for greatest distance between nodes, at the expense of lowest supportable data rate. We used QPSK almost exclusively in Demonstration 3 field trials since the XG transmit power was low.

2) Wideband Detector

A low-noise programmable high bandwidth detector

provides an estimate of power spectral density over 100 MHz with frequency resolution of down to 12.5 kHz. The detector was used to detect the presence of nearby XG nodes as well as legacy radios. If XG nodes are close by and radiating, the detector, made by Rockwell-Collins, detects the RF signature of an OFDM waveform. Legacy radios were detected using similar energy detection (radiometric) algorithms.¹ The detector's range is 30-2500 MHz, samples at 18 GHz/sec; has a user settable resolution bandwidth of 12.5, 25, 50, 100, or 200 kHz. It can detect a weak signal in the presence of strong interferers: its SFDR is +70 dB over the entire input range. Its third-order intercept point (IIP3) is +10 dBm. Noise figure is typically 12 dB. Rapid internal signal processing allows an 8192 bin x 14 bit FFT to be computed in 1000 microseconds. It has a variety of baseband interfaces: 100-base-T Ethernet, USB, and serial port. The output data is either a Fast Fourier Transform (FFT) or digitized serial. The user can select from a variety of windowing techniques: Hamming, Hanning, rectangular, Blackman-Harris, and Bartlett. A key feature of the detector is its low power and size. It can operate at less than 3W of power, and takes up only 14 in³.

3) Transceiver

A wide bandwidth IF/RF/IF transceiver was custom made for SSC. IF frequency is 13.5 MHz, and RF frequency is 225-600 MHz. It too is a compact, low power device. The transceiver supports all bandwidths required by the WiMAX modem, i.e., 1.75, 3.5, 7, and 10 MHz.

The transceiver was designed to be used with a 30W external high power amplifier (HPA). The XG Phase III demo used only 20 dBm to cut down on integration time and to meet schedule constraints. This resulted in fairly low range between XG nodes, on the order of hundreds of meters, as shown in Fig. 2. Future XG development phases will use higher transmit power and wider frequency ranges.

The OFDM waveform has a peak to average ratio of around 6 dB. This requires the use of a linear amplifier whose peak power rating is at least 6 dB higher than the average power.



Figure 2. Six XG vans in caravan formation.

The wideband antenna is a discone with a ground plane 'top hat', as shown in Fig. 3. It has good wide-bandwidth performance at VHF/UHF frequencies. Its antenna gain pattern is a down tilting azimuthally invariant donut.

¹ Better detection methods using feature detection and classification are planned as part of XG's Technology Maturation process.



Figure 3. XG van with external discone antenna and dipole antenna for Wi-Fi backhaul telemetry.

4) General Purpose Processor

A general purpose computer was used to integrate all of the other elements together, and to coordinate operations among the modem, Rockwell detector, and transceiver as shown in Fig. 1. The computer contained specially developed XG-unique software containing detection, networking, and spectrum policy software libraries of functions. A GPS sensor is shown in Fig. 1 because time and GPS location coordinates were used for test purposes.

The hardware for one XG node is shown in Fig. 4. Each metal cart has strapped to it all of the electronics required for one XG node. This picture shows six XGs side by side, undergoing network testing at SSC's laboratory.



Figure 4. XG node hardware.

C. Mobile Vans

The XG node was positioned in the back of a van so that an operator could access the computer easily for system configuration setting changes, as shown in Fig. 5 and Fig. 6.



Figure 5. Each XG node was hardware settable inside the minivan at the beginning and end of every test.

Power conditioning became an important auxiliary system that made the difference between success and failure for XG. Tests in mid-2006 showed that when the rack of XG equipment was powered by inverters attached to the automobile engine, engine noise leakage through the inverter raised the noise level into the front end of the sensitive transceivers by 4-6 dB. In order to lower the engine noise leakage, the XG equipment was powered by DC batteries, which then passed DC into an inverter that converted DC to AC usable by computers and other electronic equipment. The DC batteries were attached to the car engine's alternator. The motor engine was kept running all day to maintain a continuous supply of power to the XG nodes.

Not all inverters proved adequate. Some inverters did not provide enough AC power to the equipment. Others were too noisy to be used close to RF front ends. This method of power conditioning was adopted by legacy radio nodes, who faced similar problems.



Figure 6. XG van interior. The inverter is shown on the bottom of the figure.

IV. TEST DESCRIPTION

A. Legacy Radios

A variety of military and commercial radios were used to test XG's performance. These included:

- AN/PSC-5
- AN/PRC-117
- EPLRS
- MicroLight
- ICOM
- FRS CMR5

The AN/PSC-5 manpack (Fig. 7) is a mobile 5 W tactical area data/voice radio used for tactical command and control to Corps and Division levels, and is also used by Special Operations Forces (SOF). It is capable of being used for satellite communications, but is mostly used in a tactical terrestrial line of sight (LOS) and beyond line of sight (BLOS) mode by the Army. It can transmit 16 kb/sec into a 25 kHz RF channel. We used it at 400 mW, its lowest power setting. The PSC-5 manpacks were used with COMSEC gear. The radio performance was measured with bit error rate (BER) test equipment, as shown in Fig. 8.



Figure 7. AN/PSC-5 military radio (Source: http://www.hayadan.org.il/BuildaGate4/portals/hayadan/imagesP/sub51/5134 97479-L-psc5d.jpg)



Figure 8. AN/PSC-5 instrumented with BER test equipment.

The AN/PRC-117 is a transportable 10 W 16 kb/sec tactical radio used by joint services for tactical area terrestrial voice and data communications as well as satellite communications. See Fig. 9. Some variants of the PRC-117 can be used for air/ground communications, and can be used from 30 to 512 MHz. We used it at 1 W transmit power over a 25 kHz RF bandwidth. The PRC-117s were used with COMSEC gear. BER test equipment used to test link quality is shown in Fig. 10.



Figure 9. PRC-117 military radio (Source: http://www.specwargear.com/images/meu-satcom%201.jpg)



Figure 10. PRC-117 military radio with BER test equipment.

The Enhanced Position Location Radio Service (EPLRS) radio is a transportable frequency hopping radio that can be used for both data transmission and for non-GPS position location, using a high chip rate pseudo-noise sequence to determine position locations of other radios. See Fig. 11Figure 11. It has many modes of operation. We used it to transmit 700 mW, its lowest power setting. EPLRS radios were used with COMSEC gear.



Figure 11. EPLRS military radio.

The MicroLight radio is a Raytheon developed extension of EPLRS into a much smaller form factor. It can be used with laptop computers. It's the size of a public safety radio, with half the thickness of a normal police/fire handheld radio. It's capable of a wider range of frequencies than EPLRS. It is not frequency approved for use outside of EPLRS bands. Fig. 12 shows a MicroLight with power conditioning system in plastic container below the ruggedized laptop. The MicroLight is the standalone unit to the right of the laptop.



Figure 12. MicroLight military radio.

The ICOM radio is a commercial-class public safety transportable radio powered by a car, and is mounted under the dashboard of a car and powered by 13.5V out of a car's alternator. It can transmit voice only at up to 30 W. See Fig. 13.

The Family Radio Service (FRS) band radio is a hand held walkie talkie used in the 462.5625-467.7125 MHz. Transmit power varies depending on whether the FRS radio is used in the (lower) GMRS bands or in the upper FRS bands. We used the FRS radios for logistical coordination among moving XG vehicles and among non-cooperative transmitters and receiver vehicles. The GMRS frequencies' usable distance between radios was about 6 km. Although the test team used FRS radios as backups to the base's trunked radios, a lightning storm knocked out the cell towers of the base's trunked radio system, and service was not restored as the trunked radio system was being discontinued.

Fig. 13 shows ICOM and FRS radios, controlled by SSCdeveloped ATE. The ICOM is the unit to the right on the top shelf. The hand held FRS radio is the yellow and black walkie talkie in the plastic container to the left of the top shelf of the Faraday shield.



Figure 13. ICOM and FRS radios with computer controlled SSC-developed automated test equipment.

B. Ft. A.P. Hill Test Range

DARPA arranged to use the Night Vision Labs/Drop Zone test range at Fort A.P. Hill in Bowling Green, Virginia, approximately 140 kilometers south of Washington, DC.

The drop zone is roughly 2 km x 3.5 km area of clear land surrounded by forest. A north to south runway is in the middle of the drop zone, used for landing light aircraft and helicopters. We were not permitted to cross this runway or to use it. Two roads in the drop zone were used: Mosby Road and Vaughan Road.

Fig. 14 shows the Drop Zone. Mosby Road runs north to south. It is paved for about 0.8 km to the south, then turns into a hard-packed dirt road the rest of the way north. Vaughn is also a hard-packed dirt road that runs N-S in parallel to Mosby Road Vaughn Rd is much bumpier and has deeper gullies than does Mosby Road.

Gullies represent areas where radio line of sight stops. There was so much attenuation of signals at the bottoms of some gullies that we had *hidden node* problems. The bottoms of the gullies were 10-13 meters below the peaks, and terrain undulations were such that gully bottoms were separated by perhaps two to three hundred meters at the closest.

The XG vans were confined to using these roads. They did not go off-road during the demonstration. See Fig. 15.



Figure 14. Satellite view of Ft. A.P. Hill's drop zone, Bowling Green, VA. The drive path is shown, as well as waypoints and NC radio locations.



Figure 15. Drop zone: observation building, locations of military radio pairs, and notional locations of three XG 2-node mobile networks on the drive route.

C. Legacy Radio Locations

Legacy radios were static for the duration of the Demonstration 3 tests. They were positioned so as not to cause interference to one another. Distances between receive and transmit radios were carefully controlled so that receivers were at edge of coverage. Link quality was a sensitive indicator of in-band interference when receivers were far enough away from transmitters so that one or two dB of added in-band noise would cause bit errors or affect link quality. Table 1 shows latitude and longitudes of legacy radios.

Table 1 Waynoint Locations for XG Drive Tests									
#	Latitude		Longitude				Altitu	de Comments	
1	38	08	822	77	21	306	[it]	beginning of drive path	
2	38	09	076	77	21	747	229	Mosby Road Memorial - top of hill	
3	38	09	159	77	21	996	207	Mosby Road and Vaughn Road intersection (north side)	
4	38	09	411	77	22	289	227	Access point - middle of runway (dirt road intersection)	
5	38	09	814	77	22	555	242	end of runway	
6	38	10	129	77	22	857	233	Gully - detection zone boundary of EPLRS	
								Turn around point - Solar panel/weather observation site	
7	38	09	010	77	21	963	221	Intersection of Vaughn Rd and a branch road	
8	38	08	931	77	21	759	230	Top of hill - visibility to VIP demo building	

Legacy radio networks were forced to behave in nonstandard ways in order to induce XG radios to cause interference while driving by silent and undetectable legacy receive-only radios. One legacy radio was an active transmitter, while the other radio in the network was receiveonly. This was done in order to show potential interference more easily. This had the disadvantage of artificially increasing the number of XG error events.

> NOTE: We believe that there would have been far fewer XG error events if legacy radios behaved as they normally would have, i.e., if legacy radios in a network were allowed to transmit as well as receive.

D. Backhaul Architecture

An 802.11 Wi-Fi wireless network was used to transport telemetry data back to the Observation building. The backhaul architecture block diagram is shown in Fig. 16. IEEE 802.11G Wi-Fi units were selected for maximum range.

XG networks consisted of base station radios (WiMAX modems configured as base stations) or subscriber radios (WiMAX modems configured as subscribers). An XG network's base station was equipped with a Wi-Fi antenna and Wi-Fi modem. XG nodes were numbered 1 through 6, with odd units configured as base stations (for Scenario 1 tests²) and even units configured as subscribers (always).

The XG networks used a 'push' data architecture, whereby every XG network 'pushed' link quality data back to the Observation building once per second.



Figure 16. Wi-Fi backhaul telemetry architecture.

Legacy radio networks consisted of pairs of radios, one of which had a Wi-Fi antenna mounted on the roof of its vehicle. Legacy radios monitored link quality using either bit error rate (BER) or IP packet throughput measurement software called IPERF. Telemetry data was transported back to the observation building for data fusion and display.

Legacy radio networks used a 'pull' system of data dissemination, which involved a server at the observation building querying every legacy Wi-Fi node for data.

Once data was gathered at data servers in the Observation building, they were time aligned to account for computer clock offsets and then handed over to display handling servers.

² They were configured as subscribers during Scenario 2 tests.

Display handling routines created three kinds of displays:

- 1. A moving map display
- 2. Legacy network link quality moving map (BER vs. time, IPERF quality vs. time)
- 3. XG network link quality (link up/down vs. time)

An example of a moving map display is shown in Fig. 17. Legacy radio locations are shown overlaid on top of an aerial view of the Drop Zone. They are static, since legacy radios never move for the duration of the tests. Their color is also static. Color represents frequencies used by radios, and legacy radios either do not change frequencies or, in the case of the PRC-117 radios, change frequencies according to a script. The PRC-117 radios hopped between two frequencies every ten seconds. All other legacy networks stayed on one frequency. XG nodes can move spatially, and could also change color when they were in frequency adaptive modes.



Figure 17. XG Moving Map Display.

E. Legacy Radio Locations

Table 2 shows legacy radio site locations (north to south), as well as frequency of operation and signal characteristics.

Table 2

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Legacy Radio Site Locations (North to South)							
Legacy Radio		Frequency	Latitude	Longitude	Comment		
EPLRS	TX	422.75 MHz	38.2836° N	-77.6480° W	Northern-most radio network		
	RX		38.1702° N	-77.3848° W			
PRC-117	TX	369 MHz (10	38.1656° N	-77.3797° W			
	RX	seconds) 374 MHz (10 seconds)	38.1593° N	-77.3729° W			
Microlite	TX/RX	433 MHz	38.1591° N	-77.3728° W			
			38.1591° N	-77.3728° W			
PSC-5	TX	356 MHz	38.1436° N	-77.3566° W	Southern-most radio network		
	RX		38.1459° N	-77.3510° W			
Jammer	ТХ	(All)	Observation building	Not a radio Network.			

F. DARPA Go/No-Go Criteria

In order to advance to successive phases of the DARPA contract, Shared Spectrum had to pass a series of DARPA go/no-go criteria. These are listed in Table 3.

Table 3 DARPA go/no go Criteria

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Category	Criteria	Specification						
NO HARM: Causes no harmful interference to Non-XG systems	Abandonment Time Interference Limitation	Abandon a frequency ≤ 500 msec Maintain ≤ 3 dB SNR at a protected receiver						
XG WORKS: Forms and Maintains Network Connectivity Dynamically	Network Formation / Rendezvous Time Network Join Time Channel Re-Establishment Time	Establish 2-hode XC network in ≤ 5 sec Establish 6-hode XC network in ≤ 30 sec Joha node to an existing XC network in ≤ 5 sec Reestablish a 6-hode XC network in ≤ 500 msec						
XG ADDS VALUE: Reduces Spectrum Mgmt Setup Time	Use of pre-assigned frequencies	No pre-assigned frequencies						
(increases deployment flexibility) and increases Spectrum Access (communications capacity)	Spectrum Re-use	≥ 60% spectrum occupancy with 6-node XG network						

G. Pre-Test Procedures

Unintentional jammers were present at Ft. A.P. Hill. We did not have time to identify who the interferers were, or where they were, as we had no radio direction finding (DF) equipment. We did, however, have a Blackbird unit, which is a very fast spectrum analyzer capable of storing a few minutes' worth of spectrum analyzer sweeps to give time/frequency waterfall curves. An SSC 'Sentinel' unit consisting of a Rockwell sensor and SSC-developed software did the same thing. We used both pieces of equipment an hour before our tests were performed. We watched all frequencies in the 325-450 MHz bands to identify the presence of unintentional jammers. If we had jammers we had to reassign frequencies to the affected radio systems to run controlled tests.

H. Scenario 1

Scenario 1 tested three separate, non-coordinated XG mobile networks. Each XG network had two nodes. There were three parts to Scenario 1:

- 1. Baseline
- 2. Scenario 1a: XG networks in nonadaptive mode, show interference
- 3. Scenario 1b: XG networks in adaptive mode, should not interfere

Scenario 1 took approximately 28 minutes.

1) Baseline

Legacy network behavior was baselined for two minutes before XG tests began. During this time, real time displays of legacy network BER and IPERF (link quality) data were displayed and time aligned. XG radios and jammers were kept off. Link performance was at its best.

The PRC-117 radio switched frequencies every ten seconds. The ICOM radio was turned on and left on for the duration of Scenario 1.

XG nodes were at their original positions before the beginning of the baseline pre-test.

2) Scenario 1a: Three XG networks, Non adaptive mode

Scenario 1a began after two minutes of baseline data were taken, Every XG radio was set to use one frequency in nonadaptive mode in order to purposely interfere with legacy radio networks. Each XG radio network was assigned a different frequency which targeted a specific legacy network. XGs were driven over a pre-assigned route.

The purpose of Scenario 1a was to validate that the test setup is operating correctly, and that XG movement through the drive route could be detected by legacy radios if XG radios failed to detect and avoid legacy radios.

XG radios were separated by 100-200 meters between nodes in a network. XGs moved throughout the drive route at about 40 kph. Drive time for Scenario 1a was approximately 11 minutes.

XG radios are capable of tuning to any unoccupied frequency (subject to the XG policy restrictions). However, the XG frequency plan used in Scenarios 1 and 2 restricted XGs to operate over only six frequencies which were permitted by Special Temporary Authorizations (STAs). We used frequencies that had the lowest noise shown during pre-test frequency monitoring. It happened that these were the same for all three days of the test. This frequency table was typed into each XG so that the XGs were permitted to use only those frequencies.

The drive pattern for each XG network is shown in Fig. 14 and in Fig. 15.

XGs 1 and 2 were assigned the same frequency as EPLRS. They began in the south, far away from EPLRS and outside of its interference area. (At XG transmit power of 20 dBm, the interference radius was about 0.4 km.) They move north until they interfered with EPLRS.

XGs 3 and 4 were assigned the same frequency as the MicroLight. They began in the middle of the drop zone, almost collocated with MicroLight radios. They cause interference to the MicroLight as soon as they turn on. (At XG transmit power of 20 dBm, the interference radius was less than 0.1 km.) They drive a circular route around the MicroLights so as to cause interference to the MicroLights at regular intervals.

XGs 5 and 6 were assigned the same frequency as one of the PRC-117 frequencies. They began at Waypoint 6, north of the PRC-117 receiver, in a gully and out of detectable LOS of the PRC-117 receiver. (At XG transmit power of 20 dBm, the interference radius covered almost the entire drop zone. The only time the PRC-117 receiver was not able to detect a cofrequency XG emission was when XG was in a gully, and out of LOS of the PRC-117.) Therefore, at the beginning of Scenario 1a, XGs 5 and 6 did not interfere with the PRC-117. As soon as they began moving out of the gully, they were visible to the PRC-117 receiver. They moved south, through Waypoint 5, and ended at Waypoint 4, close to the PRC-117 receiver. Note that the PRC-117 network ping ponged back and forth between two frequencies. This resulted in XGs causing interference only half the time - the time that the PRC-117 was co-frequency with the XGs.

3) Scenario 1b: Three XG networks: Adaptive mode

Scenario 1b began after all XGs completed their drive paths and returned to the initial waypoints of Scenario 1a.

The purpose of Scenario 1b was to show that XGs were

capable of detecting and avoiding frequencies of legacy radios and of each other.

Every XG radio was switched to adaptive mode. Each network was permitted to use any frequency within the frequency table. The same drive path was used as in Scenario 1b.

Drive time for Scenario 1b was approximately 11-12 minutes.

When an XG's path was traced and colors were assigned to its frequency of operation, a figure such as that shown in Fig. 19 and Fig. 20 was displayed. Such a figure was very useful. When an XG ran out of frequencies, it could not transmit. This was shown as a red color. (It could also turn red when an XG node stopped transmitting for other reasons, such as transceiver loss of frequency lock or a computer or modem malfunction. Troubleshooting and diagnosis were required to tell the difference.) In addition, when an XG was operating at the same frequency as a victim receiver it was traveling close to – this might indicate an interference event.

I. Scenario II

Scenario 2 tested one large XG mobile network. Each XG network had four to five nodes. A jammer hopped through all of XG's operational frequencies in order to show XG's responsiveness to not just static transmitters using one frequency, but also a constantly hopping jammer. There were three parts to Scenario 2:

- 1. Baseline
- 2. Scenario 2a: XG network in nonadaptive mode, show interference
- 3. Scenario 2b: XG network in adaptive mode should not interfere. During the second half of the Scenario 2b drive test, the XG vehicles were given commands to move from the audience of Government witnesses and other observers.

Scenario 2 took over an hour.

1) Baseline

Legacy network behavior was baselined for two minutes before XG tests began. During this time, real time displays of legacy network BER and IPERF (link quality) data were displayed and time aligned. XG radios were kept off. Link performance was at its best.

The PRC-117 radio switched frequencies every ten seconds. The jammer was turned on. It hopped through all six frequencies once every minute, with a dwell time of 10 seconds per frequency. The ICOM radio was turned off (this is different from Scenario 1). The ICOM frequency was used as a 'safety' frequency in case other frequencies were unavailable.

XG nodes were at their original positions before the beginning of the baseline pre-test.

2) Scenario 2a: One large XG network Non adaptive mode

Scenario 2a began after two minutes of baseline data were taken. The XG radio network was set to non-adaptive mode, and forced to continuously transmit at 374 MHz, one of the PRC-117's frequencies. Since the PRC-117's interference radius was almost the entire drop zone, the XG network should interfere with the PRC-117 victim receiver every ten seconds. (The PRC-117 receiver was also seeing interference ten seconds of every minute by the jammer.)

The XG nodes formed a convoy with 20 meter spacing between nodes. They began at the PSC-5 receiver in the south part of the drop zone, and moved north until they were halfway up Mosby Road to Waypoint 4, which was close to the PRC-117 receiver. Drive speed was between 40 and 50 kph.

The purpose of Scenario 2a was to validate that the test setup was operating correctly, and that XG movement through the drive route could be detected by (one of the) legacy radios if XG radios failed to detect and avoid legacy radios.

XG radios were separated by 20 meters between nodes. XGs moved throughout the drive route at about 40-50 kph. Separation between nodes was important, and resulted in slower drive speeds than for Scenario 1. Drive time for Scenario 2a was approximately 10 minutes.

 Scenario 2b: One Large XG Network, Adaptive mode Scenario 2b began after the XG convoy reached Waypoint
4.

Scenario 2b had multiple objectives:

- Demonstrate that XGs were capable of detecting and avoiding frequencies of legacy radios. This reinforced what was shown in Scenario 1b.
- Demonstrate that a 4-5 node XG network could abandon a channel quickly and could rendezvous at another channel within 500 msec.

Every XG radio was switched to adaptive mode. Each network was permitted to use any frequency within the permitted frequency table.

The driving was divided into two parts: During the first few minutes, the XG caravan moved north, passed the PRC-117 transmitter, got close to the EPLRS receiver, and turned around and began heading south. After that, the XG caravan was given driving directions by the audience.

Drive time for Scenario 2b was approximately 30-40 minutes.

J. VIP Audience Displays

The XG demonstrations were conducted live. While DARPA and Shared Spectrum presenters were describing XG nodes and the behavior of XG networks, the audience saw three panels of information, as shown in Fig. 18.



Figure 18. Real time VIP demo displays. The left panel shows real time XG performance parameters on top and XG location and frequency (as a color) on the real time map of the drive path. The right panel shows real time NC military radio BER (or link quality) vs. time. The middle panel is a static briefing slide

The central panel was a static briefing slide with a verbal description of the test and the expected outcomes.

The right panel showed the "Do no harm" aspect of XG radios. It showed four live charts of five minutes of BER versus time. If XG radios interfered with legacy radios, the radios' BER would spike up. Elevated bit error rate levels were usually correlated with XG radios in close proximity to legacy radio receivers. When XG radios were in non adaptive mode, the BER rates would rise when XGs drove close by. When XG radios were in adaptive mode, the BER rates would usually only rise slightly, if at all. The difference was so remarkable that the audience wanted to control the XG radio vans and have them drive by victim radios again.

Note: Some legacy radios did not have bit error rate capabilities, and so showed a delivered-packet quality metric Errored bits or packets could be caused by XG radios or by random noise events, which are not uncommon on a military base.

The left panel had four subpanels: One was a moving map display of the XG radio locations and the locations of the victim radios, as shown in Fig. 19 and Fig. 20. The other three panels showed XG network communications performance versus time.

XG network communications performance required three panels, one for each network. Throughput was low or high, depending on whether legacy radios (or other XGs on the same frequency) interfered with them or not. When interference was unacceptably high, the XG radios would change to other frequencies. The throughput remained high even through frequency switching, which showed that XG communication sessions could be successfully maintained even though they were constantly switching frequencies.

The moving map display showed XG radio networks in different colors. When the XGs were in nonadaptive mode, the XGs could drive close to the legacy radios without changing frequencies, and would cause interference, which showed up as BER interference spikes in the right panels. When the XGs were in adaptive mode, the XGs would change frequencies well before causing interference, and the BER interference curves would remain flat, showing that XG did not cause interference.

A third thing the colored moving nodes showed was that

when two XG nodes of different networks but sharing the same frequency approached each other, they detected each other and deconflicted, that is, they moved to different frequencies automatically. This was another phenomenon of the XG network that the audience wanted to see repeatedly. The automatic deconfliction of networks was of great interest to DoD spectrum managers.

As a side note, creating this moving map display proved to be rather difficult due to the infrastructure required (GPS, real time moving map display software, but it helped immensely to prove the point of XG's non-interference.



Figure 19. Sample XG scenario 1 performance: frequency vs. location.





V. CONCLUSIONS

A six-node XG network and three two-node XG networks were tested using four test scenarios: two were "without XG adaptation" and two were "after adaptation." The audience, members of the U.S. government's military and spectrum management officials, was able to see clearly how XG could adapt to the local interference landscape and share frequencies rapidly and with little to no interference with existing legacy military radio systems. This demonstration showed that DARPA concepts of frequency sharing in a mobile environment are possible with today's technology.

Results of the demonstration tests are given in a companion paper. [1]

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He also apologizes for the length and verbose nature of the paper, but must fall back to Pascal's famous excuse, that the paper is longer than usual because he lacked the time to make it shorter.

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