SYSTEM CONSIDERATIONS FOR AUTONOMOUS DYNAMIC SPECTRUM UTILIZATION

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ABSTRACT

The issue of spectrum scarcity is both a pragmatic and perceptual problem. The real problem is not so much a lack of spectrum but an apparent scarcity that comes from poor utilization caused by spectrum use policy that is fast becoming archaic due to the natural progress of technology and growth of societal use requirements. DARPA's XG (NeXt Generation) program asserts that spectrum capacity could conceivably be increased by an order of magnitude. This would be accomplished by "opportunistic spectrum access" via an iterative four-phase cycle of "sense, characterize, react, and adapt." While the latter two phases of react and adapt and the implicit policy definition and management have their own challenges, the really hard part technologically will be the initial two phases of sense and characterize, requiring spectrum ingest resources proportional to the demands of the application environment (commercial, military, etc.) and greater than may now be considered by many. There are a number of techniques that are in current use for sensing and characterizing spectrum usage. Some are under open discussion such as the radio measurement techniques being used by researchers as well as being considered by the IEEE 802.11k Radio Resource Measurement task group for the LAN community. Other techniques are proprietary, being part of commercial products used for signal classification. Still others are used by the military for information warfare. The fundamental principles intrinsic in each of these domains are noted here to help establish appreciation for the "sense and characterize" problem. This is a small step toward software defined radios becoming cognitive, because a cognitive radio almost always would include sufficient intelligence to evaluate its RF environment, determine what part of the spectrum it wants, then determine the waveform best suited to that environment—and then learn from those decisions. This will not only take a lot of hardware and software resources, but also a new way of viewing the spectrum, the network, and computing.

1. INTRODUCTION

Two significant problems that are confronting wireless communications vis à vis spectrum use in general and military communications in particular are scarcity and deployment difficulty. The *deployment* problem is a process problem; i.e., frequency allocation is fixed and is done so by complex collaboration and coordination between countries and systems, respectively. The issue of spectrum *scarcity* is both a pragmatic and perceptual problem that can best be appreciated by a casual glance at the US Frequency Allocation chart as published by the US Department of Commerce's National Telecommunications and Information Administration (NTIA) [1] and reproduced in Figure 1 (it is recommended the reader download their own copy and enlarge it). The usable spectrum is indeed finite, but the current way its usage is deployed—providing new services with their own respective slice of the spectrum—is what needs amelioration. Referring again to Figure 1, it does not seem possible that the current dissemination licensing model driven by a fixed view of the spectrum can continue, especially as more and wider band services will be vying for this fixed and (seemingly) scarce resource.

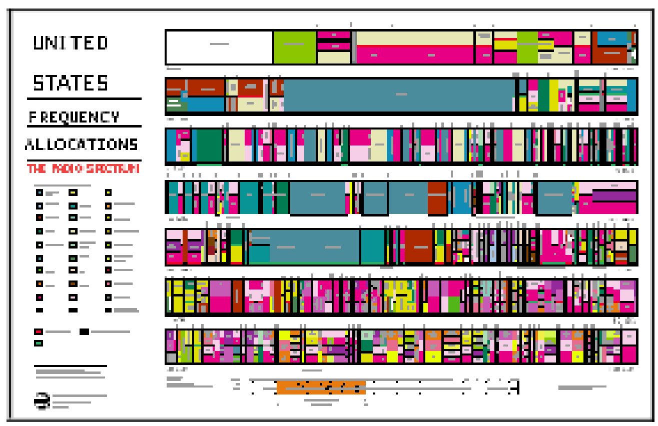

Figure 1. A seemingly crowded spectrum.

Fortunately, recent research efforts to characterize actual spectrum usage in both urban and rural areas have shown that more spectrum is available than conventionally realized. DARPA asserts that the upper bound of usage is only 6% as shown in the sanitized PSD of Figure 2 [2]. Polson suggests the number is in the range of 7%-14% [3]. Other recent studies report findings on the same order of magnitude [4-6].

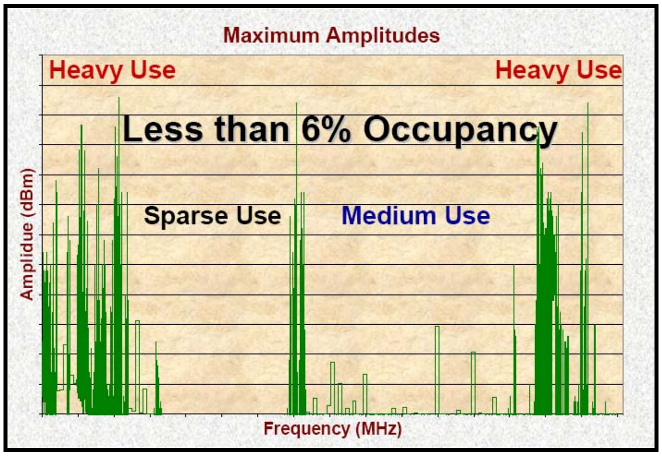

Figure 2. One view of the actual availability of spectrum.

Georgia Tech's Radio Spectrum Engineering Lab has done some of the most extensive spectrum use measurement. Usage results in the 400 MHz to 7.2 GHz range are shown in Table 1 (from p. 19 in [6]).

Table 1. Spectrum usage over 400 MHz to 7.2 GHz

	Urban	Rural
Usage in time & space	6.5%	0.8%
Vacant spectrum	77.6%	96.8%
Amount of "white space"	5.3 GHz	6.6 GHz

So, the real problem is not so much a lack of spectrum but an apparent scarcity that comes from poor utilization resulting from spectrum use policy that is fast becoming archaic due to the natural progress of technology and growth of societal use requirements.

This is an area undergoing active research and analysis and many have contributed to defining and developing this area of research and technology. In the commercial industry this includes:

- IEEE 802.11k[1]—The task group chartered to define Radio Resource Measurement enhancements to provide interfaces to higher layers for radio and network measurements for the wireless LAN community.
- Vanu—The first commercial company to be recognized by the FCC as a provider of Software Defined Radio (SDR) [7].
- SDR Forum[2]—An international and technically active consortium of academia, government, and industry working together to further SDR technology and usage, especially the Cognitive Radio Working Group, which is focused on dynamic spectrum reuse.
- Open Management Group (OMG)[3]—A not-for-profit consortium that primarily produces and maintains computer industry specifications for interoperable enterprise applications such as CORBA and UML, but also shepherds specifications for SDR-related standards like the Software Communications Architecture on behalf of the JTRS program (see next paragraph).

In the DoD community, leading influences include:

- JPO—The Joint Tactical Radio System (JTRS) Program Office, who is ambitiously striving to satisfy "diverse warfighter communications needs through software programmable radio technology"[4]. The core of achieving this aggressive goal is the Software Communications Architecture ("SCA") and a number of "Core Frameworks" that implement the SCA for the various JTRS phases ("Clusters").
- DARPA—The "NeXt Generation" ("XG") Program[5] that is specifically focused on dynamic spectrum reuse and other SDR-relevant programs such as Adaptive Cognition-Enhanced Radio Teams (ACERT) that was just announced[6].

Of particular interest and focus in this paper is DARPA's XG program, which asserts that due to how spectrum is being wasted (cf. Figure 2), spectrum capacity could conceivably be increased by an order of magnitude. This would be accomplished by "opportunistic spectrum access." The basic idea is that a radio device first "senses" the spectrum of interest, then identifies and characterizes primary users that are present. Combining this emitter awareness with knowledge of regulatory policies applicable to its locality and spectrum, the radio device determines spectrum opportunities in frequency, time, and possibly code, and then transmits in a self-limiting manner so as not to interfere with primary users. This is an iterative process as illustrated in Figure 3 (adapted from Figure 1 in [8]).

Architecting solutions to the two phases of "Sense & Characterize" is a technology-driven problem that is signal processing intensive in general and with system considerations exceeding those of a non-cognitive radio in particular. Addressing the other two phases of "React & Adapt" is a policy-driven problem that is knowledge engineering intensive. Radio devices that can achieve such opportunistic spectrum will require SDRs with a lot of

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[1] The 802 is a large working group with multiple task groups. The base website is grouper.ieee.org/groups/802/11.
[2] Home page is on the web at www.sdrforum.org.
[3] Home page is on the web at www.omg.org.
[4] Home page is on the web at jtrs.army.mil.
[5] Home page is on the web at www.darpa.mil/ato/programs/xg/index.htm.
[6] Announcement is on the web at www.darpa.mil/ipto/solicitations/open/05-37_fboprint.htm.

capability, probably more than they could now deliver in the form factor envisioned.

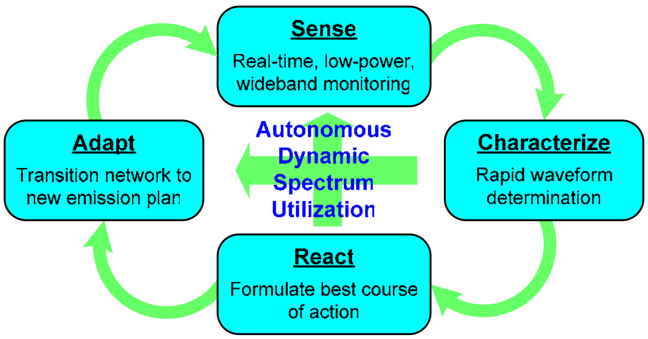

Figure 3. DARPA's envisioned XG dynamic spectrum reuse iterative flow.

Developing spectrum-aware SDR for DoD for use in tactical communication has similar and unique challenges compared to spectrum-aware SDR in general. The differentiating feature of a military radio is that it is used in many different locations and situations that range from use during peaceful times at home to wartime abroad. While the former stresses the efficiency of the spectrum use while fulfilling the defined mission within the framework of DoD and government regulation, the latter stresses reliability of communications, resistance to intercept and detectability (LPI/LPD), and security. Nevertheless, requirements of the exceptionally high capability to ingest and characterize/interpret the signals constituting the war fighter radio landscape are the same in both situations with the application of these capabilities shifting from observing the rules imposed by regulatory bodies to monitoring friendly and enemy radio activities with less regard for those rules.

While realizing that the higher cognitive levels of a radio [9] are important integral parts of an XG radio, this paper is concerned with the spectrum sensing (ingest) and characterization capabilities of the military radio within the DoD framework and is organized along these lines. To address these in this paper, we will first define the problem of spectrum-aware SDR for the military as done in this section. We will then look at current approaches to spectrum awareness. Understanding the performance requirements will allow us to begin to grasp what the system requirements are going to be for SDRs that are spectrum-aware. Finally, we will draw high level conclusions about what will be required to move current SDR technology forward towards and beyond being spectrum-aware. Useful references will be provided as well.

2. APPROACHES TO "SENSE & CHARACTERIZE"

There are a number of techniques that are in current use for sensing and characterizing the spectrum. Some are under open discussion such as the radio measurement techniques being evaluated by the IEEE. Other techniques are proprietary, being part of commercial products used for signal classification. Still others are classified as used by government programs for information warfare. The fundamental principles intrinsic in each of these domains are noted here to help establish appreciation for the "sense & characterize" problem.

The commercial wireless community is very interested in SDR, cognitive radio, and dynamic spectrum reuse. This includes such traditional players as Philips [10, 11] and Nokia [12] and newcomers like Vanu[7] [7, 13]. Many are participating in the IEEE 802.11 standardization efforts for wireless local area networks [14], of which Task Group k (TGk) is of interest here [15]. The 802.11 TGk develops radio resource measurements as an extension to the IEEE 802.11 standard. The goal of this extension is to provide tools by which a radio device can measure and assess its RF environment and take corresponding action; i.e., to "sense & characterize." Perhaps the key measurement for agile radios is the Medium Sensing Time Histogram report, which was developed by the authors of [16]; they view their work as an extension of 802.11 or UWB under consideration by the XG way of radio resource regulation and management. This technique is illustrated in Figure 4 (from Figure 4 in [16]). MATLAB simulations by the authors of demonstrate how opportunistic spectrum access during a low traffic load can be available shown in Figure 5 (from Figure 5 in [16]) or not so available as in a high traffic load scenario as shown in Figure 6 (from Figure 6 in [16]; see next page).

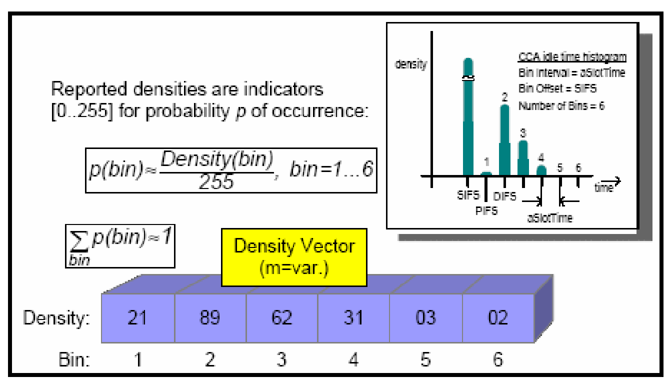

Figure 4. IEEE 802.11k's Medium Sensing Time Histogram.

[7] Home page is on the web at www.vanu.com.

It should be noted that these measurement techniques provide no information about the signals that are present, just that they exist—and at that moment in time. More advanced usage detection algorithms do more than just compute a coarse PSD estimate as shown above in Figure 4 through Figure 6. The approach presented in [6] is more sophisticated than the Medium Time Sensing Histogram, because it has the characteristics delineated in the following list:

- Identifies spectral usage by
    - Using the profile of spectral emitters
    - Accounting for the effects of the propagation environment
- Makes no assumptions about emitters or frequency plans
- Does not use time averaging, which can overlook intermittent signals

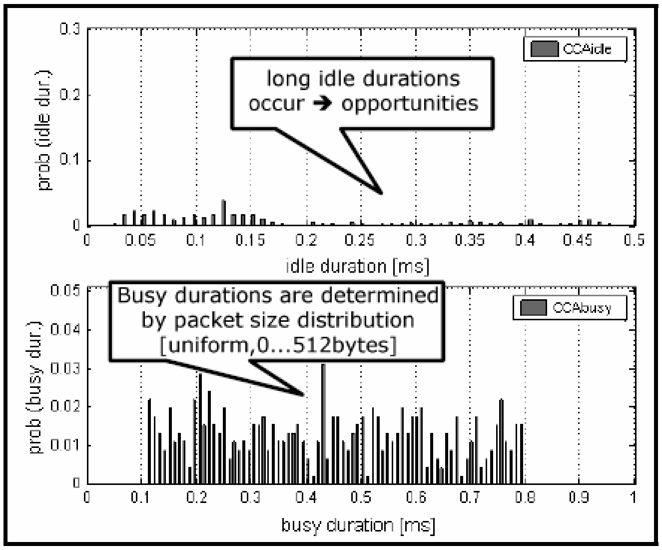

Figure 5. Medium Sensing Time Histogram for a low traffic load; opportunistic spectrum access is available.

Spectrum-aware SDR deployed for military communications will require greater capability than that needed for a simple wireless LAN or spectrum usage experiment. The military must not just identify spectrum usage, but also identify the actual signals. Whether at peace or at war, the military radio has to characterize the ingested signals with speed and precision resulting in determining the type of transmitting equipment, the user and the location of the signal. During wartime, the use of such information is important for determining the electronic order of battle. In the future, this information will be crucial for the new XG radios performing within the framework set by DOD, NTIA and FCC. All of the available knowledge about the signal needs to be used for these purposes, which is a lot more than "Is there spectrum available?" and "Can I have some, please?" This includes:

- Is the detected signal analog or digital?
- What is the modulation type?
- What is the transmitter's geographical location?
- What are the signal's parameters (frequency, time, etc.)?
- If possible, is the user of the radio emitting specific emitter identification (SEI) data in the signal?

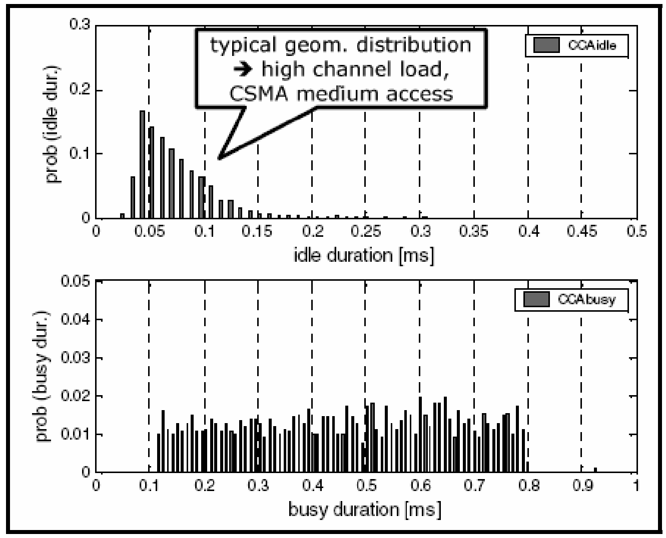

Figure 6. Medium Sensing Time Histogram for a high traffic load; opportunistic spectrum access is *not* available.

In some cases, it is possible to determine all of the information just on the basis of frequency and geographical location. For instance, the use of the spectrum by cellular companies is very static and this knowledge can be obtained from the database in the radio or obtained from the higher levels of an appropriate knowledge base in a wireless fashion. Hence, the knowledge of the frequency and the location should be sufficient to determine the modulation type and user of the signal. Sometimes, knowledge of the modulation type is required, as in the case of the unlicensed ISM bands where multiple uses of the band exist, including several Wi-Fi modulations and cordless telephones.

Commercial products exist to perform signal identification. One that is advertised in the public domain is the RRP-1307 Signal Recognizer[8] from Radix Technologies in Mountain View, CA, which is advertised to provide rapid classification with high accuracy of the modulations tabulated in Table 2.

SDR researchers at Canada's Communications Research Centre[9] assert that other spectrum-aware reasons

[8] More information is on the web at www.radixtek.com/signal_class.htm.

[9] More information is on the web at www.crc.ca/en/html/crc/home/home.

for performing signal analysis in order to monitor the radio spectrum. They provide an integrated set of software tools to perform a number of spectrum-aware tasks, including signal analysis (cf. Table 3). This tool suite is collectively known as Spectrum Explorer[10].

Table 2. Modulations the Radix RRP-1307 can recognize.

Analog	Digital	
AM	BPSK	4FSK
FM	QPSK	8FSK
USSB	π/4-DQPSK	00K
LSSB	8PSK	4PAM
DSB-SC	16PSK	16QAM
Morse	2FSK	32QAM
Carrier	MSK*	64QAM
Noise	3FSK	256QAM

*MSK includes GMSK & SQPSK

Table 3. Modulations the CRC Spectrum Explore's Communication Signal Analyzer can recognize.

Analog	Digital
AM	BPSK
FM	QPSK
DSB-SC	π/4-QPSK
Carrier	MPSK
Noise	FSK

3. SYSTEM REQUIREMENTS OF SPECTRUM-AWARE SDRS

As the level of required spectrum detail of which to be aware increases, so do the system requirements of the platform. Implementation of 802.11k radio measurement tools like that illustrated in Figure 4 will not require much in the way of real estate or processor memory. But when a wider spectrum and/or more spectral/signal details must be determined, the system requirements and implementation demands increase. Just for purposes of illustration, the block diagram for the CRC Spectrum Explorer is shown in Figure 711.

[10] More information is on the web at www.crc.ca/en/html/spectrum-explorer/home/home.
[11] From the product description on the web at www.crc.ca/en/html/spectrum-explorer/home/solution.

The full Spectrum Explorer including the Signal Analyzer mentioned above, is a flexible software application suite or framework running on a Windows workstation and combined with high performance receiver and digital interface hardware. The combination is a SDR receiver capable of sophisticated spectrum monitoring measurement and analysis. Hardware and software setups as used for the spectrum measurement studies mentioned above vary but are on the same order of magnitude with respect to form factor.

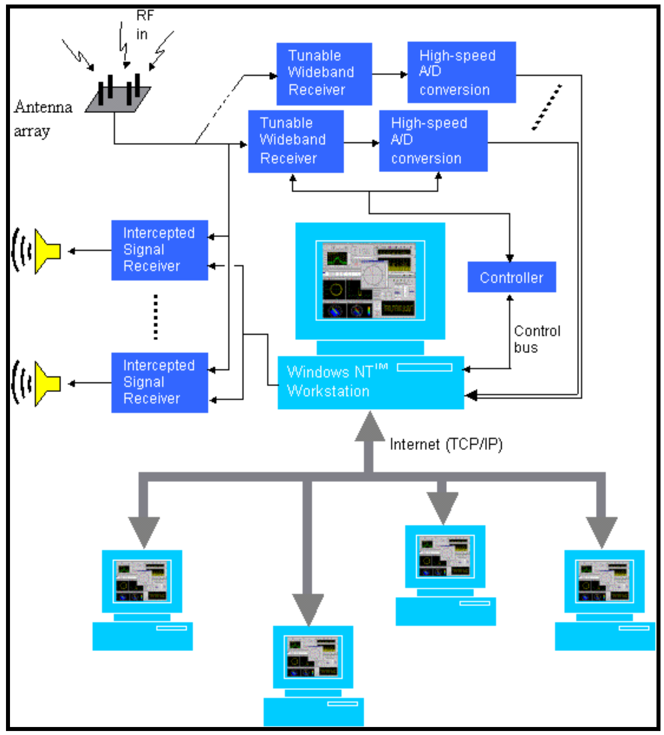

Figure 7. Block diagram of CRC's Spectrum Explorer.

When the problem is enlarged to include not just 802.11k-type spectrum sniffing, wider spectrum energy detection, or signal classification, then the implementation requirements just grew to require a hardware/software codesign comparable to sophisticated receiving systems, which are typically comprised of a VME rack of receivers, tuners, and processing boards. Certainly technology will reduce this form factor constraint with time, but it is doubtful that alone would be sufficient. A more synergistic and flexible solution is required to provide SDRs with acceptable form factors that can be spectrum aware and more as the mission requires. The JTRS and its associated SCA has been a remarkable effort, but hindsight being 20/20 shows us the importance for even more forethought, especially in providing adequate flexibility in architecture. The JTRS SDR was envisioned to be a discrete channel radio that could process legacy waveforms. Consequently, it is very challenging to make SCA-based SDRs spectrum aware or adaptive. The architecture practically demands mapping each channel to its own computing resource, even if a given channel has a lightweight waveform to process. All its unused computational bandwidth cannot be tapped for other tasks. Ideally, military SDRs could be adaptively networked in an ad-hoc fashion and the aggregate unused compute resources be leveraged for spectrum aware tasks, as well as spectrum adaptive tasks.

4. CONCLUSION

Clearly spectrum aware—and adaptive—radios are a stepping stone to cognitive SDRs. “Cognitive radio” like many coined terms is an overloaded term, but a cognitive radio almost always would include sufficient intelligence to evaluate its RF environment, determine what part of the spectrum is available, then determine the waveform best suited to that environment—and finally learn from those decisions. This will not only take a lot of hardware and software resources, but also a new way of viewing the spectrum, the network, and computing. Those who understand and appreciate spectrum ingest, and software architecture will have the clearest vision.

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System Considerations for Autonomous Dynamic Spectrum Utilization

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16 November 2005

Introduction

- Who is Argon ST?
  - Member of the SDRF and participating in Cog Radio WG & SIG
- The spectrum problem
  - Perception or reality—or both?
- The DARPA XG approach
  - "Sense & characterize"
- System considerations
  - Relevant COTS technologies
- Conclusion

www.argonst.com

Corporate Overview

Was created by the September 2004 merger of

SenSyTech Inc.

ARGON engineering

Created a unique C4ISR company providing a broad range of Electronic Warfare and Imaging solutions to our customers in defense, intelligence, homeland security and select international markets

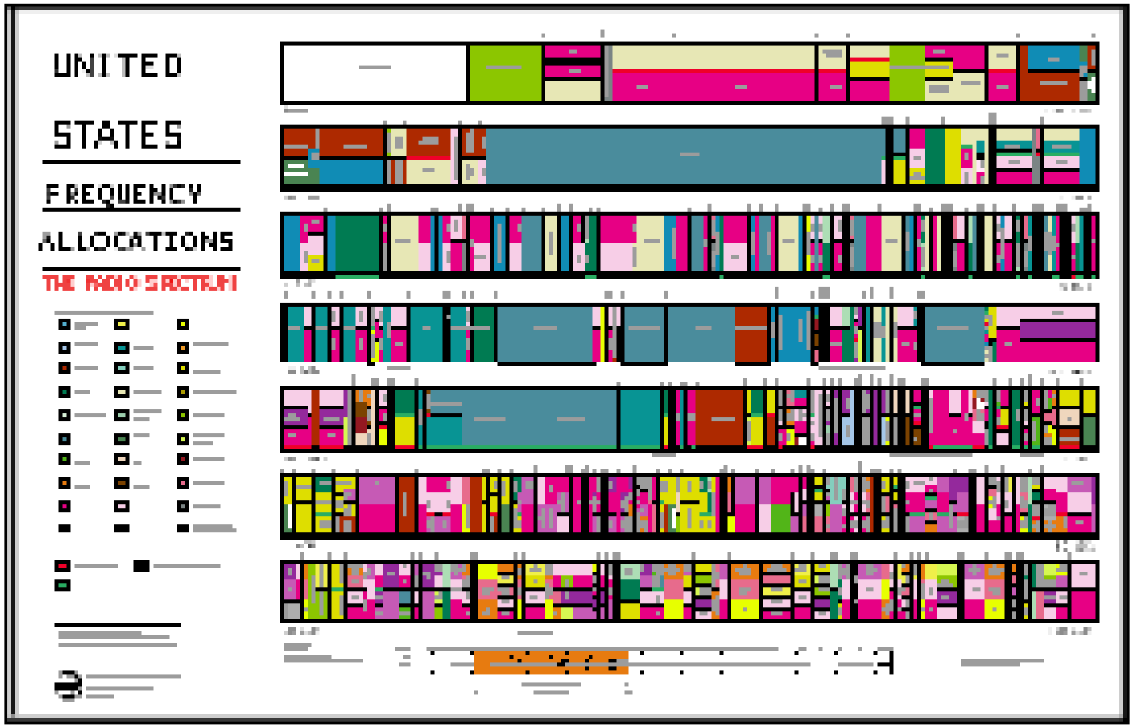
October 2005 added Radix Technologies Inc.

Radix Technologies

High performance, leading edge signal processing systems and equipment for military, intelligence community, and commercial applications. The systems have applications in reconnaissance, geolocation, anti-jamming GPS, and communications systems.

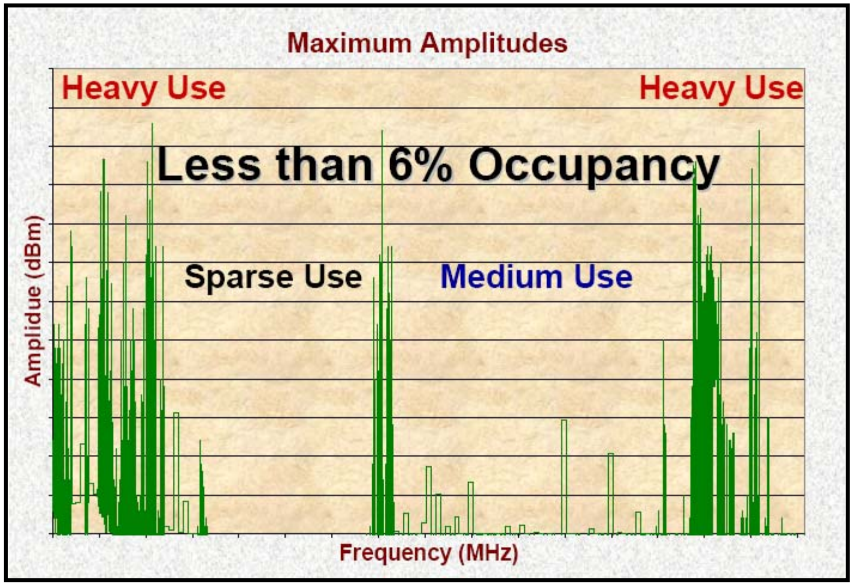
Enabling Information Dominance for America

Spectrum Scarcity for Wireless Comm: Perception, Reality, or Both?



- The ubiquitous US *fixed* frequency allocation chart
- Scarcity is a deployment *process* problem
- The problem is BOTH pragmatic & perceptual

Actual Measured Spectrum Use



- Sanitized DARPA measurements
- At last year's SDRF TC, John Polson suggested that the occupancy is more in the range of 7% to 14%

- Research results from Georgia Tech's Radio Spectrum Engineering Lab

	Urban	Rural
Usage in time & space	6.5%	0.8%
Vacant spectrum	77.6%	96.8%
Amount of "white space"	5.3 GHz	6.6 GHz

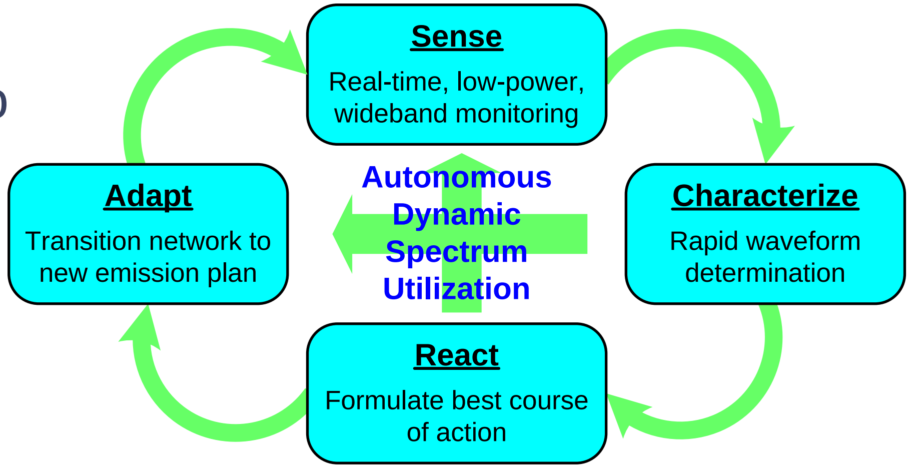
Who's Interested in Spectral Scarcity?

- Commercial world
  - IEEE 802.11k—Radio Resource Measurement
  - SDR Forum—Facilitating industrial & academic advancement
  - OMG—Software-Based Communications (SBC) Workshops & JTRS spec oversight
  - Wireless comms providers—Vanu, Philips, Nokia, et al.
- Academia
  - Georgia Tech—Spectrum utilization
  - Virginia Tech—Cognitive SDR
- US DoD
  - JTRS Program Office—Multiple programs
  - DARPA—XG & ACERT

Lots of intrest by multiple groups!

DARPA's XG Program

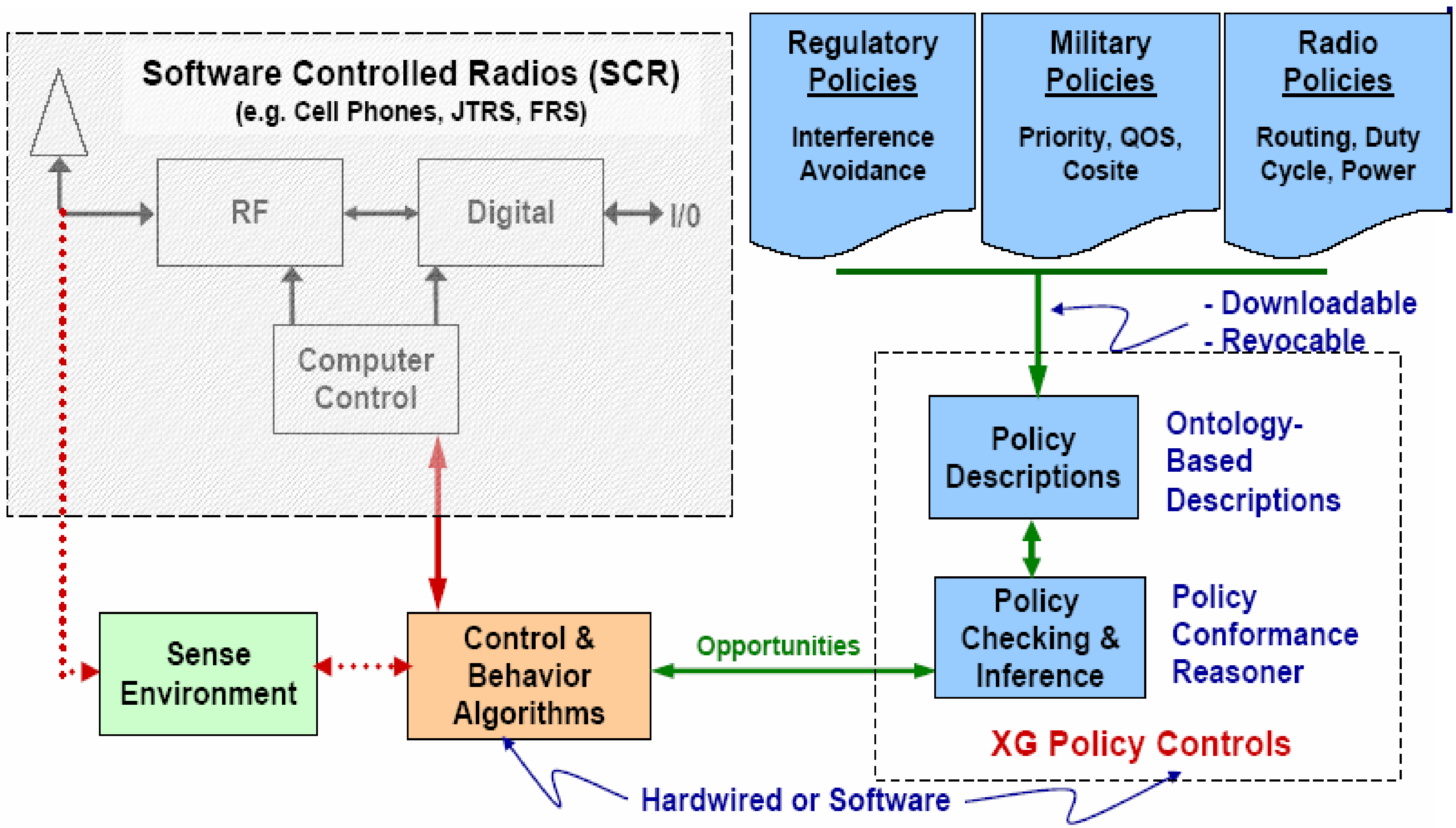
- "Actively developing the technology and system concepts to dynamically access all available spectrum"
- Goal: Demo 10x increase in spectrum access



- Combination of new spectrum-aware technologies
  - Measurements (temporal, spectral, dimensional, energy, etc.)
  - Policy-cognizant/based controls
- XG "products"
  - XG behaviors
  - Initial XG implementation

Goal: NOT a new radio, BUT set of next-gen technologies for dynamic spectrum access.

XG Program Components



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Approaches to "Sense & Characterize"

- Different communities, but similar interest
  - Commercial wireless community (Philips, Nokia, Vanu et al.)
    - Collaborative: OMG, SDR Forum, IEEE 802.11k
  - DoD
    - Classified, but still collaborative—albeit limited: OMG, SDRF, JTRS community
- IEEE 802.11 Task Group k (802.11 TGk)
  - Develops radio resource measurements as an extension to the IEEE 802.11 standard
  - Provide tools so a radio device can
    - Measure & assess its RF environment & take action
    - Very similar to "sense & characterize" idea

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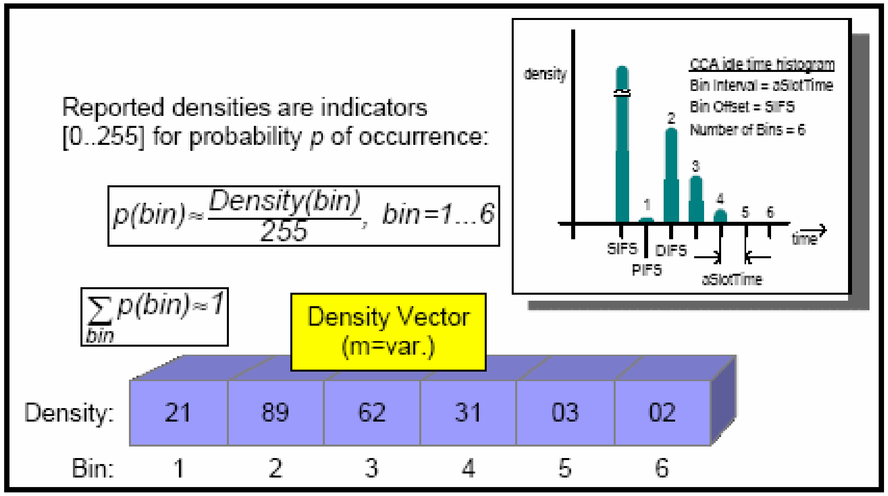
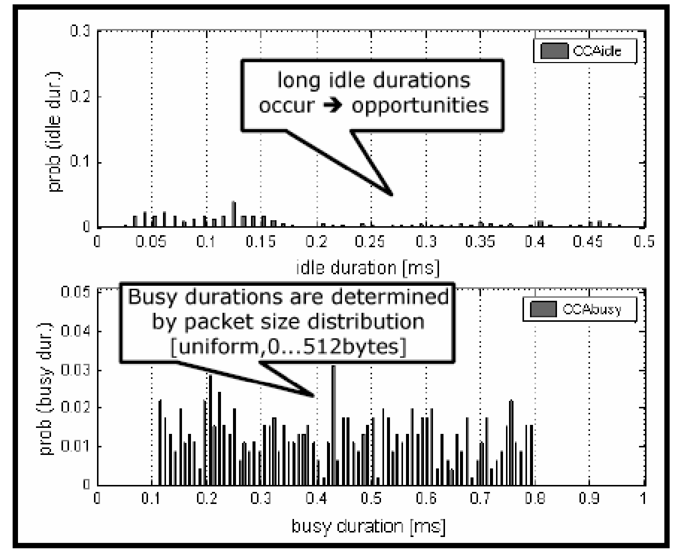
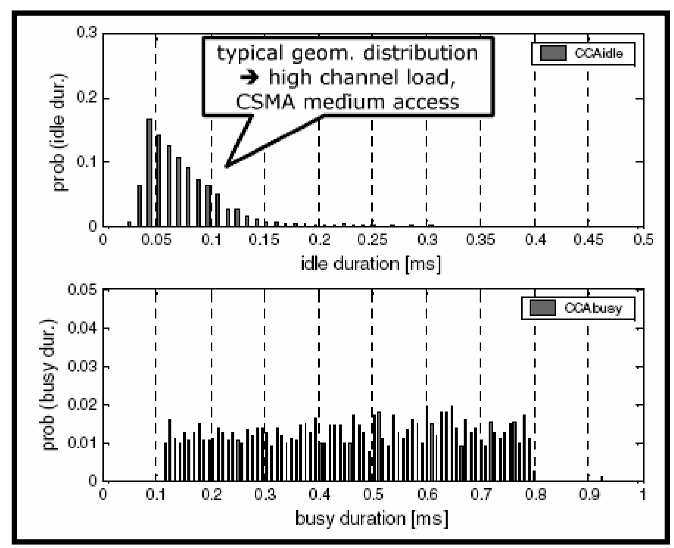
Medium Sensing Time Histogram







- Measurement technique developed by Mangold et al. at Philips Research's Wireless Comm & Networking Dept.
  - Coarse PSD estimate
  - Determine presence of signals
- Applicable to both IEEE's 802.11k and XG's UWB
- MATLAB-based simulation results illustrate technique's utility to both groups

SDR '05

Needed Refinements

- Medium Sensing Time Histogram is limited
  - Momentary snapshot in time
- More sophisticated approach by Petrin & Steffes of Georgia Tech:
  - Identifies spectral usage by…
    - Using the profile of spectral emitters
    - Accounting for propagation environment
  - Makes no assumptions about emitters or frequency plans
  - Does not use time averaging
    - Can cause some signals to be overlooked
- Basic spectrum-aware SDR methodology:
  - Is there spectrum available?
  - May I have some please?
- Spectrum-aware SDR in military wireless comm have greater demands
  - Not just spectrum usage
    - ID the actual signals
      - Analog or digital?
      - Modulation type?
      - Signal parameters?
    - Geolocation of transmitter?
    - Specific emitter identification (SEI)?
  - Work within the framework set by the DoD, NTIA, FCC, and other governing agencies
- Do it all in real-time or near-real-time

System Requirements of Spectrum-Aware SDRs

- Systems currently exist that can perform varying degrees of spectrum aware processing
  - Commercial
  - Military
- Understanding level of effort—and amount of hardware & software—to accomplish this helps to frame the system requirements of a spectrally aware SDR
  - A couple examples of commercial products
  - Hardly exhaustive—but information is difficult to obtain

Commercial Examples

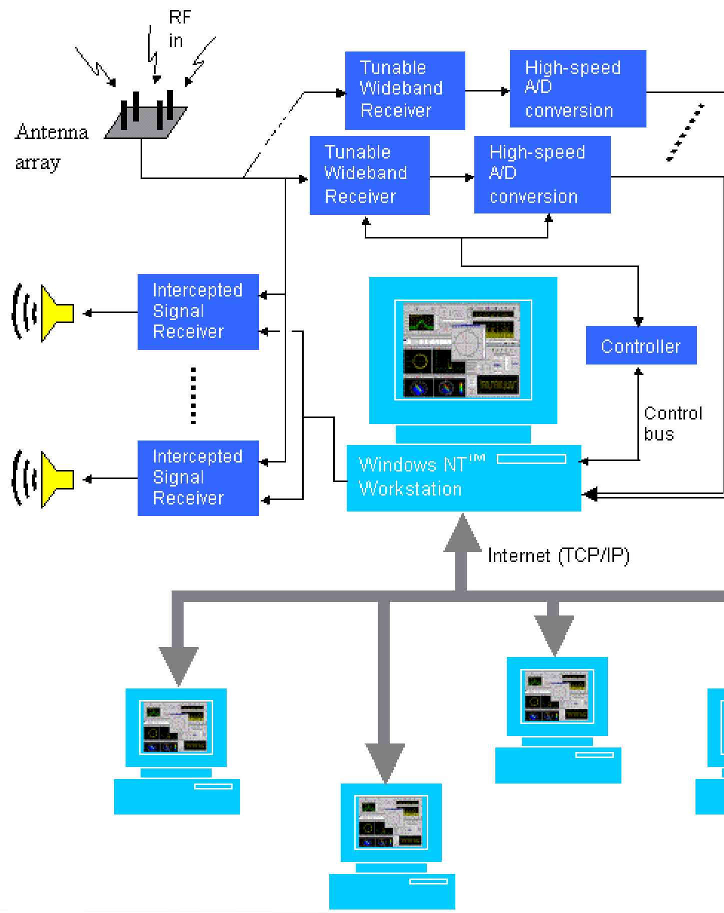
RRP-1307 Signal Recognizer
(Radix Technologies)

Analog	Digital	
AM	BPSK	4FSK
FM	QPSK	8FSK
USSB	π/4-DQPSK	00K
LSSB	8PSK	4PAM
DSB-SC	16PSK	16QAM
Morse	2FSK	32QAM
Carrier	MSK*	64QAM
Noise	3FSK	256QAM

*MSK includes GMSK & SQPSK

That's a lot of software

Spectrum Explorer
(Canada's Communications Research Centre)



Analog	Digital
AM	BPSK
FM	QPSK
DSB-SC	π/4-QPSK
Carrier	MPSK
Noise	FSK

That's a lot of hardware

Conclusions

- Spectral sniffing for commercial hand-held wireless comm is achievable
  - Not a technology issue as much as a policy issue
- Mil-grade spectral awareness requires a lot more:
  - Spectrum sniffiing—but sniffing of a very wide spectrum
  - Signal classification & geolocation—and more….
  - Current implementations are on the order of VME racks
- Developing systems that can deliver dynamic spectral utilization—within SWAP constraints desired—will require DARPAesque XG-type technologies
  - Spectral ingest is the technological lynchpin