Dynamic Spectrum Access Technology

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Introduction

- Intricacies of Spectrum Utilization and Allocation
- Current Spectrum Occupancy Measurements
- Alternatives to Current Spectrum Management
- Dynamic Spectrum Access (DSA) Technology
- SSC Current DSA Technology Development Areas
- DSA Works, Causes No Harm, and Adds Value
- Conclusions
Intricacies of Spectrum Utilization and Allocation
Increasing Demands on Spectrum Usage
Require Better Spectrum Utilization

• Demand for spectrum is increasing
  – More users, more services, more data

• Amount of spectrum is constant

• Need efficient spectrum utilization
  – To accommodate spectrum users without harmful interference
Current Spectrum Management is Inefficient

• Current approach is based on a static spectrum pre-allocation that divides spectrum by
  – Frequency
    • Radio service
  – Location
  – Time

• Static pre-allocation must consider worst-case scenarios
  – To limit any potential interference

• As a result, all spectrum has been allocated
  – That is on paper…
Static Allocation is Inefficient
Static Allocation is Really Inefficient

Restrictions differ across countries
Real-time Utilization Differs Drastically

<table>
<thead>
<tr>
<th>Spectrum Occupancy in Chicago and New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chicago</strong></td>
</tr>
<tr>
<td><strong>New York City</strong></td>
</tr>
<tr>
<td>PLM, Amateur, others: 30-54 MHz</td>
</tr>
<tr>
<td>TV 2-6, RC: 54-88 MHz</td>
</tr>
<tr>
<td>Air traffic Control, Aero Nav: 108-138 MHz</td>
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<tr>
<td>Fixed Mobile, Amateur, others: 138-174 MHz</td>
</tr>
<tr>
<td>TV 7-13: 174-216 MHz</td>
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<tr>
<td>Maritime Mobile, Amateur, others: 216-225 MHz</td>
</tr>
<tr>
<td>Fixed Mobile, Aero, others: 225-406 MHz</td>
</tr>
<tr>
<td>Amateur, Fixed, Mobile, Radiolocation, 406-470 MHz</td>
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<tr>
<td>TV 14-20: 470-512 MHz</td>
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<tr>
<td>TV 21-36: 512-608 MHz</td>
</tr>
<tr>
<td>TV 37-51: 608-698 MHz</td>
</tr>
<tr>
<td>TV 52-69: 698-806 MHz</td>
</tr>
<tr>
<td>Cell phone and SMR: 806-902 MHz</td>
</tr>
<tr>
<td>Unlicensed: 902-928 MHz</td>
</tr>
<tr>
<td>Paging, SMS, Fixed, BX Aux, and FMS: 928-968 MHz</td>
</tr>
<tr>
<td>IFF, TACAN, GPS, others: 960-1240 MHz</td>
</tr>
<tr>
<td>Amateur: 1240-1300 MHz</td>
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<tr>
<td>Aero Radar, Military: 1300-1400 MHz</td>
</tr>
<tr>
<td>Space/Satellite, Fixed Mobile, Telemetry: 1400-1525 MHz</td>
</tr>
<tr>
<td>Mobile Satellite, GPS, Meteorological: 1525-1710 MHz</td>
</tr>
<tr>
<td>Fixed, Fixed Mobile: 1710-1850 MHz</td>
</tr>
<tr>
<td>PCS, Asyn, Iso: 1850-1990 MHz</td>
</tr>
<tr>
<td>TV Aux: 1990-2110 MHz</td>
</tr>
<tr>
<td>Common Carriers, Private, MDS: 2110-2200 MHz</td>
</tr>
<tr>
<td>Space Operation, Fixed: 2200-2300 MHz</td>
</tr>
<tr>
<td>Amateur, WCS, DARS: 2300-2360 MHz</td>
</tr>
<tr>
<td>Telemetry: 2360-2390 MHz</td>
</tr>
<tr>
<td>U-PCS, ISM (Unlicensed): 2390-2500 MHz</td>
</tr>
<tr>
<td>ITFS, MMDS: 2500-2686 MHz</td>
</tr>
<tr>
<td>Surveillance Radar: 2686-2900 MHz</td>
</tr>
</tbody>
</table>

Our measurements show that real-time measured occupancy in many bands is significantly less than what’s allocated.


Current Spectrum Occupancy Measurements
• Objective to identify spectrum bands with low occupancy
  – Occupancy = the amount of spectrum detected above a certain received power threshold level

• Numerous locations
  – Vienna, VA, Tysons Corner, VA, Great Falls, VA, Arlington, VA, Greenbank, WV, New York City, Chicago, Dublin, Ireland
• Although allocated, not every TV channel is used
  – Even in the urban area such as New York city
Alternatives to Current Spectrum Management
• Static spectrum management is too restrictive
  – Opportunities exist in frequency, time, and geography

• Dynamic spectrum management *observes* and *responds* to the *opportunities* in *real-time*
  – Possible approaches
    • Real-time location-based allocation
    • Real-time sensed-based allocation
    • Hybrid of the two
Real-time Location-based Allocation
Improves Utilization but at Large Cost

- Assumes a location-aware system
  - Radios continuously report their location

- Computes necessary allocation
  - To avoid interference based on location
  - Centralized, hierarchical or peer-to-peer protocol

- Advantage
  - Better utilization - real-time response to topology changes

- Disadvantage
  - Privacy – radios must report their location
  - Complex – must consider the entire environment as a whole
  - Restrictive – must assume worst-case propagation for each radio
Real-time Sensed-based Allocation
Improves Utilization Even More and at Lesser Cost

- Assumes a spectrum-aware system
  - Radios can sense their spectral environment
    • Radios can exchange the sensed data

- Identifies and uses only available spectrum
  - Radios find and use spectrum holes
  - Radios evacuate frequencies if other signal is detected

- Advantage
  - Better utilization – real-time response to spectral changes

- Disadvantage
  - Signal detector – radios must be able to sense and analyze spectrum to detect spectral holes and other signals
Dynamic Spectrum Access (DSA) Technology

for

Real-time Sensed-based Allocation
Dynamic Spectrum Access (DSA) Technology

- Software-defined, cognitive radio that senses and detects available spectrum through user-defined policies
  - High communication availability and reliability
  - Defeat hostile and friendly jamming
  - Reduced propagation loss by selecting “best” frequency
  - Enables robust spectrum pooling with peer users
  - Efficiently and safely use encumbered spectrum
    - No connection or modification with legacy systems
    - Proven interference avoidance techniques
  - Obtain additional spectrum at a low cost
  - Improve the capacity and flexibility of existing communication systems
  - Service providers lease from spectrum owners
  - Licensees lease spectrum to third party service providers

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Current DSA Technology Development Areas
DARPA XGDSA System Operation

1. Spectrum Policy Analyst builds and edits OWL-based policies based on prior international coordination and force commanders goals.

2. Spectrum manager downloads and updates policies to all XG-enabled radios.
   - Minimal interference to Country A's users or to non-XG enabled coalition forces.
   - No interference protection to Country B's users.
   - Low interference (<-150 dB/Hz) to non-networked XG-enabled radios.
   - Available bands: f1-f2, f3-f4 (only if connected to network),…

3. XG-enabled radios measure spectrum occupancy.
   - Periodically report findings to "Fusion Nodes".

4. Disconnected XG-enabled radio.

5. "Fusion Nodes" provide spectrum hole probability grid tables to all XG-enabled nodes.

6. XG-enabled nodes use policies, own measurements and probability grid tables to access spectrum to meet policy-specified interference requirements.

Disconnected XG-enabled nodes use policies, own measurements to access spectrum (within limited bands) to meet policy-specified interference requirements.

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XGDSA System Components

• Any radio
  – With multi-frequency support
    • For using different frequencies
  – With sensing capability
    • For detecting spectral holes
    • For detecting non-cooperative signals
  – With compliance support
    • For compliance with regulatory requirements
    • For compliance with network requirements
• Ultra-sensitive detectors identify unused spectrum
• The **Rendezvous** and **Frequency Selection** algorithms select which channels to use
• **Scheduler** manages which detectors are used, what frequency the devices use, and when the detectors and tuner/modems operate
• **Group Behaviors** use distributed spectrum occupancy measurements made by individual DSA nodes and fused across collection of nodes to provide probabilistic estimate of the geographical location of spectrum holes
• The **Policy Analyzer** validates externally created spectrum access policies for consistency and accuracy
• The **Policy Administrator** securely disseminates policies using PKI
• The **Policy Enforcer** ensures that each DSA radio adheres to the policy rules
Spectrum Access Policies Enable Interference-Free and Frequency-Agile Operation in Many Spectrum Bands

<table>
<thead>
<tr>
<th>Listen-Before-Talk based types</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBT – Same up and downlink frequencies</td>
</tr>
<tr>
<td>LBT – Different, but known, up and downlink frequencies</td>
</tr>
<tr>
<td>LBT – Different, but known, up and downlink frequencies, band plan known</td>
</tr>
<tr>
<td>LBT – TV band (TV detector)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Connectivity based types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beacon reception required to use band</td>
</tr>
<tr>
<td>Connectivity requirement for any policy (can use certain bands only if connected to Spectrum Manager)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group Behavior based types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 Group Behavior - Abandon channel if any node within certain range detects Non-cooperative signal</td>
</tr>
<tr>
<td>Type 2 Group Behavior - Determine DSA TX power based on estimated interference probability (used Belief, Disbelief, and Ignorance estimates fused with Dempster-Shafer Theory)</td>
</tr>
<tr>
<td>Node Identify restrictions (e.g., use while airborne prohibited, use only in fixed applications, Red Cross use only)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spatial types</th>
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</thead>
<tbody>
<tr>
<td>Geographic border field strength limits</td>
</tr>
<tr>
<td>Database geographic/TV coverage area based</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Temporal types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Day restrictions</td>
</tr>
<tr>
<td>Authorization for finite time duration (with periodic renewals)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Device based types</th>
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</thead>
<tbody>
<tr>
<td>Device Capability - Ability to measure second and third harmonic</td>
</tr>
<tr>
<td>Device Capability - DSA TX power spectrum density limit</td>
</tr>
<tr>
<td>Adjustable I/N Limit for any policy (- 6 dB (insignificant interference impact to Primary users), 20 dB (medium amount of interference impact to peer DSA nodes))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distributed Control based types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated policy updates if feedback indicates that existing policy is insufficient for non-interference operations</td>
</tr>
<tr>
<td>Automated policy updates notification of policy revocation or update by policy authority</td>
</tr>
</tbody>
</table>
Automated Policy Control Supports
Peer-to-Peer and Hierarchical Spectrum Control

**Equipment Data (DD1494 – NTIA/DoD) Policies**
- ~200 radio types
- Frequency range, TX power, NF, BW, ...
- Detection/false alarm rule sets – Radar pulse pattern, FM modulation, etc.
- LBT rule threshold parameter spreadsheet
- Ex: RT-1107(V)/9/WSC-3(V) operates from 225-399 MHz, 5 kHz BW...

**Regional Policies (Assignment Database)**
- Limitations of frequency range, TX power, BW
- Service (Fixed, mobile, airborne, ...)
- Frequency range, TX power, NF, BW, ...
- LBT rule time parameters
- Geographic, time limitations
- Ex: AN/GRT-022 is used from 225-320 MHz only, -6 dB I/N

**Local Party-to-Party Policies**
- Geographic, time
- Spectrum leasing limitations
- User priority
- LBT threshold and time parameters
- Ex: 440 MHz is only used occasionally for radar testing. You can use this channel if you have a monitoring system with an elevated antenna within LOS of Andrews AFB is used to detect (every five minutes) if we are using the radar transmitter or not. Only groups that I provide a "certificate" to are allowed this privilege.

**National Rules Policies (NTIA and FCC rules)**
- Geographic, time
- Spectrum leasing limitations
- User priority
- LBT threshold and time parameters
- Policy dissemination limitations
- Ex: 243 MHz used only for emergency

**OWG-Based high-level descriptive language**

**DSA System**
- DSA radio operates on all of the policies to decide "proper" operation

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Enforcing no-harm via high-level policies

Control when XG devices
• Can transmit (permission)
• Must not transmit (prohibition)

Abstract XML-encoded Policies

Multi-source, multi-policy compliance
• Situation awareness
• Policy priority levels

System Strategy Reasoner (SSR)

XG Device

Policy Conformance Enforcer

Provides a guarantee that the radio does not “break” anything by monitoring and restricting what the SSR can do.

✓ Regulators have assurance that devices access permitted spectrum only
✓ Operators have assurance that they can configure DSA properly
✓ Other users have assurance that their devices are not harmed

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Remote Components for
Authoring, Analyzing, and Managing Policies

Web User Interface
- Off-line policy configuration for groups of radios
- On-line policy management of one or more radios
- On-line performance querying of each radio
- Available now

Administration Console
- Includes policy enforcer, reasoner, manager, database library, security library, geographical library, compression library, and remote control
- Available now

XG Radio just one component in the policy framework
- Includes policy enforcer, reasoner, manager, database library, security library, geographical library, compression library, and remote control
- Available now

Authoring Tool
- Wizard and expert mode for editing policies
- Currently developing

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• Support un-trusted users and spectrum pooling
• Identified spectrum actors and spectrum access types
• Developed use cases for spectrum use, sharing, pooling, and leasing
• Defined an architecture in support of the use cases
• Focus on digital certificates
  – Re-used Web concepts for certificates
  – Multiple certificate classes
    • A and AS Classes for spectrum assignment
    • O Class for organizational allocation
    • M Class for manufacturer certification
    • C Class for command & control certification
    • R Class for granting rights to issue other certificates
Using certificates for easing regulatory requirements on certifying DSA-enabled radio devices

Before a radio is used, the radio must contain
- A or AS Class certificate specifying spectrum access restrictions
- M Class certificate specifying manufacturer’s restrictions
  - With parent R-Class certificates
→ **Policy Enforcer can decide what the radio can and is allowed to do**

- C Class certificate specifying command & control rights
→ **On-board Policy Manager can decide who has the right to add/remove policies and how much powerful the policies are**

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DSA Works, Causes No Harm, and Adds Value
• Two tracks of DARPA XG Program:
  – XG proof-of-concept
    • Criterion 1: Must do no harm
      – Channel Abandonment Time (<500 msec)
      – Interference-to-Noise Ratio
    • Criterion 2: Must work
      – Network Join Time (<5 seconds)
      – Network Re-Establishment Time (<500 msec)
      – No pre-assigned frequencies
      – Link uptime
    • Criterion 3: Must add value
      – White Space Fill Factor
      – Success in Channel Use
  – XG transition to other existing radios
<table>
<thead>
<tr>
<th>DSA 1000 / DSA 2000 / DSA 2100</th>
<th>DSA 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoD RF Board (MHz)</td>
<td>Public Safety RF Board (MHz)</td>
</tr>
<tr>
<td>DSA 1000 – Transceiver</td>
<td>DSA 2100 – High Power, Long Range</td>
</tr>
</tbody>
</table>

- DSA 1000 - Transceiver: 10 W (1 dB compression), 20-1000 MHz, Antenna diversity.

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AP Hill Field Demos

Legacy DoD Radio (fixed)  XG Radios (mobile)

Legacy DoD Radio/Test Equipment

August 2006

Legacy Radios
## AP Hill Test Metrics & Results Summary

<table>
<thead>
<tr>
<th>Metric</th>
<th>Threshold</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XG Causes No Harm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abandon Time</td>
<td>500 msec</td>
<td>100% in 465 msec</td>
</tr>
<tr>
<td>Interference Limit</td>
<td>3 dB</td>
<td>Mean: 0.16dB, Max: 0.49 dB</td>
</tr>
<tr>
<td><strong>XG Works</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Formation</td>
<td>30 sec w/ 6 Nodes</td>
<td>90%: 3.6 s; 100%: 8.68 s</td>
</tr>
<tr>
<td>Net Join</td>
<td>5 sec</td>
<td>90%: 2.07 s; 100%: 4.36 s</td>
</tr>
<tr>
<td>Net Re-Establish</td>
<td>500 msec</td>
<td>100%: 165 msec</td>
</tr>
<tr>
<td><strong>XG Adds Value</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrum Occupancy</td>
<td>60% w/ 6 Nodes</td>
<td>85% Occupancy at 83% Confidence</td>
</tr>
</tbody>
</table>

**XG Demonstrated Reliable Networking Without Harming Legacy Nodes In Dense Spectrum Environments**
• XG nodes constantly change frequency
  – Avoid Legacy signals
  – Avoid other XG signals
  – Overcome spatial and temporal changes
• XG connectivity requires
  – An available channel
  – Proper algorithm operation
Three or more nodes takes longer than two nodes because the Base Station has a delay after change frequency command to allow Subscriber queues to empty. Additional nodes take more time because of messaging delays.

“Kink” in the two node case is caused in the cases when the Base Station detects Non-cooperative and then has a delay after change frequency command to allow Subscriber queues to empty.
Participation in Trident Warrior 07 Exercise

- Installed XG on operational platform
- Achieved longest XG link to date – 14 km
- Improved rendezvous algorithm by reducing “hunting” problem when using low threshold in high ambient noise environment
- Increase XG node TX power to 10 W operation

Used slow frequency hopping signal generator located near XG 1 to simulate NC transmitter to force XG to change frequency

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Norfolk, VA, April 2007
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Airship-Ground Demonstration

- Loring, Maine - Sept 2007
- Demonstrated
  - Elevated node operation
  - Mobility
  - Link stability

- 5 km long, mobile links
- IP traffic
- Video downlink
- Airship and van both mobile

SSC “Demo 3” radio system
• Performed a set of field tests with Policy Software integrated in “Demo 3” DSA radios
  – 2 mobile nodes at Fort A.P. Hill
    • Focus on policy testing not new hardware testing

• Tested
  – Temporal constraints
  – Geospatial constraints
  – Spectral constraints
  – Priority constraints
Fort A.P. Hill Tests Showed
Geospatial and Priority-based Policy Reasoning

- **Case 3: Policy A**
  - All channels are blocked in the 1 km radius around Woodford – Windsor junction

- **Case 3: Policy B**
  - Another rule of higher priority comes into effect which allows transmission in this zone on channels 5 and 6

- **Scenario for Node 6**
  - At 11:20 am Node 6 loads Policy A while inside the circle
  - Node 6 drives inside and outside of the circle
  - At 11:46 am Node 6 loads Policy B while continuing driving in and out of the circle
  - At 12:05 pm Node 6 unloads both Policy A and Policy B

Woodford – Windsor Junction
Coordinates: 38.175018, -77.336883

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Fort A.P. Hill Tests Showed Successful
Geospatial and Priority-based Policy Reasoning (Cont)

All frequency channels are blocked by default

8) Both policies unloaded

7) Node 6 leaves the circle

6) Node 6 enters the circle

5) Policy B loaded

4) Node 6 leaves the circle

3) Node 6 enters the circle

2) Node 6 leaves the circle

1) Policy A loaded

All frequency channels are enabled

Policy B overwrites Policy A and so upper channels are enabled

All frequency channels are blocked

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Conclusions

• DSA radios provide an “order of magnitude“ improvement to wireless communications
  – Spectrum access, capacity, ease of use, reliability, jam resistance

• Policy-controlled DSA provide an “order of magnitude” improvement to frequency managers
  – Capacity, shorter or no planning periods, ease of use

• SSC is currently testing the first affordable and “fieldable” DSA radios
  – 70 radios being built

• Significant field tests in multiple environment have been completed
Thank you

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