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IEEE 802 Tutorial:
Cognitive Radio

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Cognitive Radio: What is it?

- **FCC:**
  - **A radio system whose parameters are based on information in the environment external to the radio system**
- **NTIA proposal:**
  - **A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets**
- **Extended Definition for Science and Engineering Community:**
  - **Adaptive, multi-dimensionally aware, autonomous radio system that learns from its experiences to reason, plan, and decide future actions to meet user needs**

Cognition – the act or process of knowing, including awareness, perception, memory, and judgment

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Cognitive Radio Features

Link cognition to radio

- ***Adapts:*** **adjusts transmission parameters (e.g., frequency, modulation, power) to meet requirements and goals**
- ***Senses (Awareness):*** **acquires and maintains knowledge of own capabilities, internal network state, external data (e.g., spectrum use, policy), and user needs**

Required for cognition

- ***Reasons:*** **uses reasoning (e.g., case-based, model-based) on ontology and observations to adjust adaptation goals and respond to new situations**
- ***Learns:*** **reflects on past performance to recognize conditions and react to reach goals faster over time**

Enhanced cognition

- ***Plans:*** **anticipates required future actions based on previous and current conditions**
- ***Networks:*** **leverages more than own experience to arrive at "right" decision**

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Cognitive Radio Applications

- Dynamic Spectrum Access
  - Particularly well-suited for ad hoc mobile networks
  - Level of distributed autonomy vs. centralized control
- Bridging across networks
  - Call group establishment (public safety, military, etc.)
- Multi-network selection
  - Select "best" network access
- Link optimization (modulation, power, topology)
- Connectivity / capacity / security (e.g., biometric authentication)
- Service discovery

Cognitive Radio uses automation to remove requirement for user to have detailed knowledge of how to do each of these things

Cognitive Radio Elements

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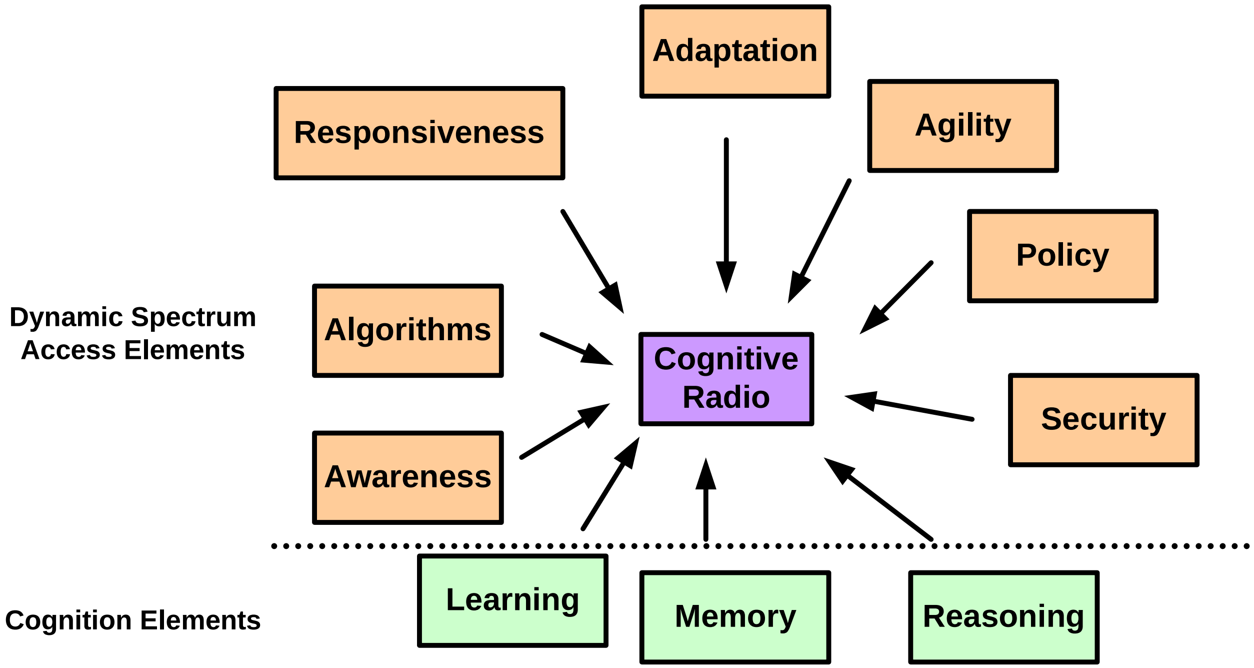

Simplified View of Cognitive IQ Levels:

- pre-cognitive: adaptive policy-based radio
- emerging: self-correcting
- developed: mistake-avoiding
- intelligent: multi-dimensionality reasoning / awareness

Adaptive vs. Cognitive Dynamic Spectrum Access

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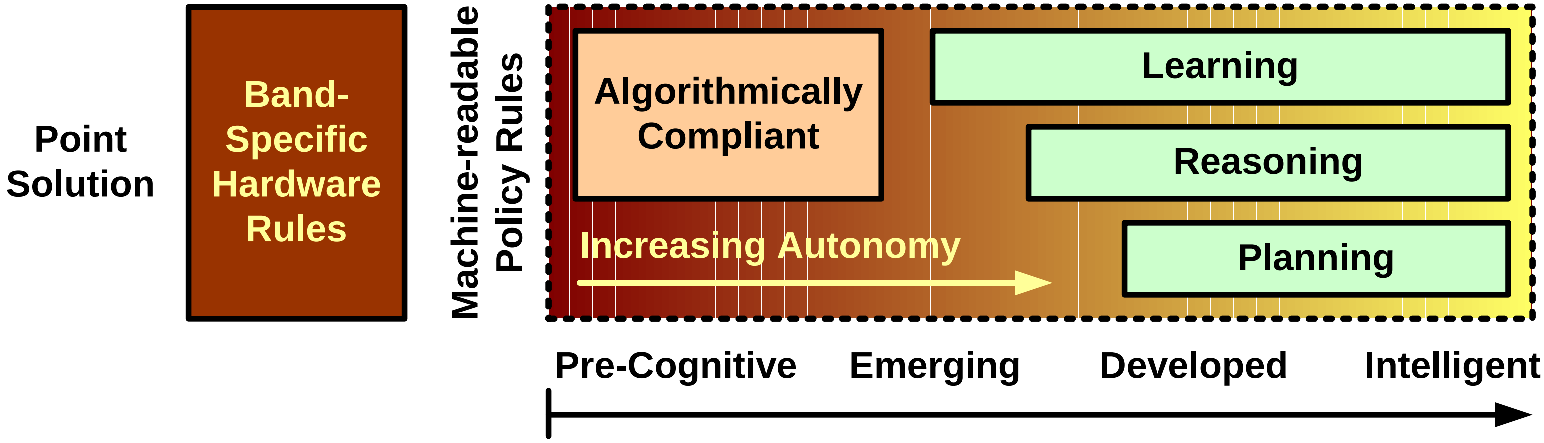
- Regulatory Policy establishes the allowed operation boundaries
  - Allowed power, interference duration, etc.
- Adaptive, spectrum-aware radio follows algorithmically encoded decision-making process to operate within allowed boundaries
  - Release spectrum, select new open spectrum, repeat until not "kicked off" selected spectrum
- Cognitive radio reasons to select the "best" solution within allowed operation boundaries
  - Assess observed situation to identify likelihood of open spectrum remaining available for longer duration to reduce required adaptation
  - Select "best" parameter combination
    - e.g., low power, wide bandwidth vs. high power, narrow bandwidth with equivalent data capacity



Anticipated Cognitive Radio Benefits for Spectrum Management

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- **For Regulator:**
  - **Significant increase in spectrum availability for new and existing applications**
  - **Streamlined licensing process**
- **For License Holder:**
  - **Reduced complexity frequency planning**
  - **Facilitated secondary spectrum market agreements**
  - **Increased system capacity (more users) through access to more spectrum**
  - **Interference-avoiding operation**
- **For Equipment Manufacturer:**
  - **Increased demand for wireless devices**
- **For User:**
  - **More capacity per user**
  - **Enhanced interoperability and bandwidth-on-demand for Public Safety and Emergency Response operations**
  - **Ubiquitous mobility with single user device across disparate spectrum access environments**

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Spectrum Management Considerations

- Definition of potential harmful interference to incumbent(s)
  - Power level (interference temperature)
  - Duty cycle
  - Persistence – avoid catastrophic interference incidents
- Band-by-band operational policy
  - Sense/adapt
  - Positive control beacon reception
  - Spectrum “order wire” control channel for cross-system coordination
  - Near-real-time agreements between primary and secondary licensees
- Spectrum etiquette requirements
  - Spectrum sensing rate
  - Spectrum hole busy marking
  - Situation-dependent aggressiveness in accessing spectrum
    - e.g., public safety emergency
- Device capabilities and limitations *{turning cognition into action}*
  - Waveform (signal-in-space format)
  - Tune time, RF tuning range, spurious emissions
  - Timing and Position accuracy
  - Antenna pattern
  - Built-in self test

Industry Forum and Professional Society Activity

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- IEEE
  - 802.22 Working Group on Wireless Regional Area Networks (WRAN) – Cognitive Radio Air Interface
  - 802.16h License-Exempt Task Group
  - DySPAN 2005 – IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (Baltimore, November 2005)
- Software-Defined Radio Forum (SDRF)
  - Cognitive Radio Technology Working Group
  - Cognitive Applications Special Interest Group (chair)
- Wireless World Research Forum (WWRF)
  - SIG1: Spectrum Topics
  - WG4: New Air Interfaces, Relay-based Systems and Smart Antennas
- ITU-R
  - WP8A: non-cellular
  - WP8F: cellular
- E2R

The wireless community is beginning to investigate dynamic spectrum access techniques

Dynamic Spectrum Sharing Radio Behaviors – State-of-the-Science

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- Spectrum Utilization
  - Coordination
  - Negotiation
  - Selection
  - Use
  - Release
  - Adaptation
- Awareness Management
  - Collection
  - Dissemination
  - Interpretation
  - Validation

Awareness Types
- Policy
- Spectrum
- Regulatory
- Commander's Intent
- Self
- Neighbor
- Mission
- Traffic (e.g., data rate, QoS)
- Network
- Environment
- Security
- Propagation
- User
- Business
- Application

Behavior – radio system action or reaction in response to internal or external stimuli under specified circumstances consistent with policy

Autonomous Dynamic Spectrum Access (ADSA): "Spectrum Hopping"

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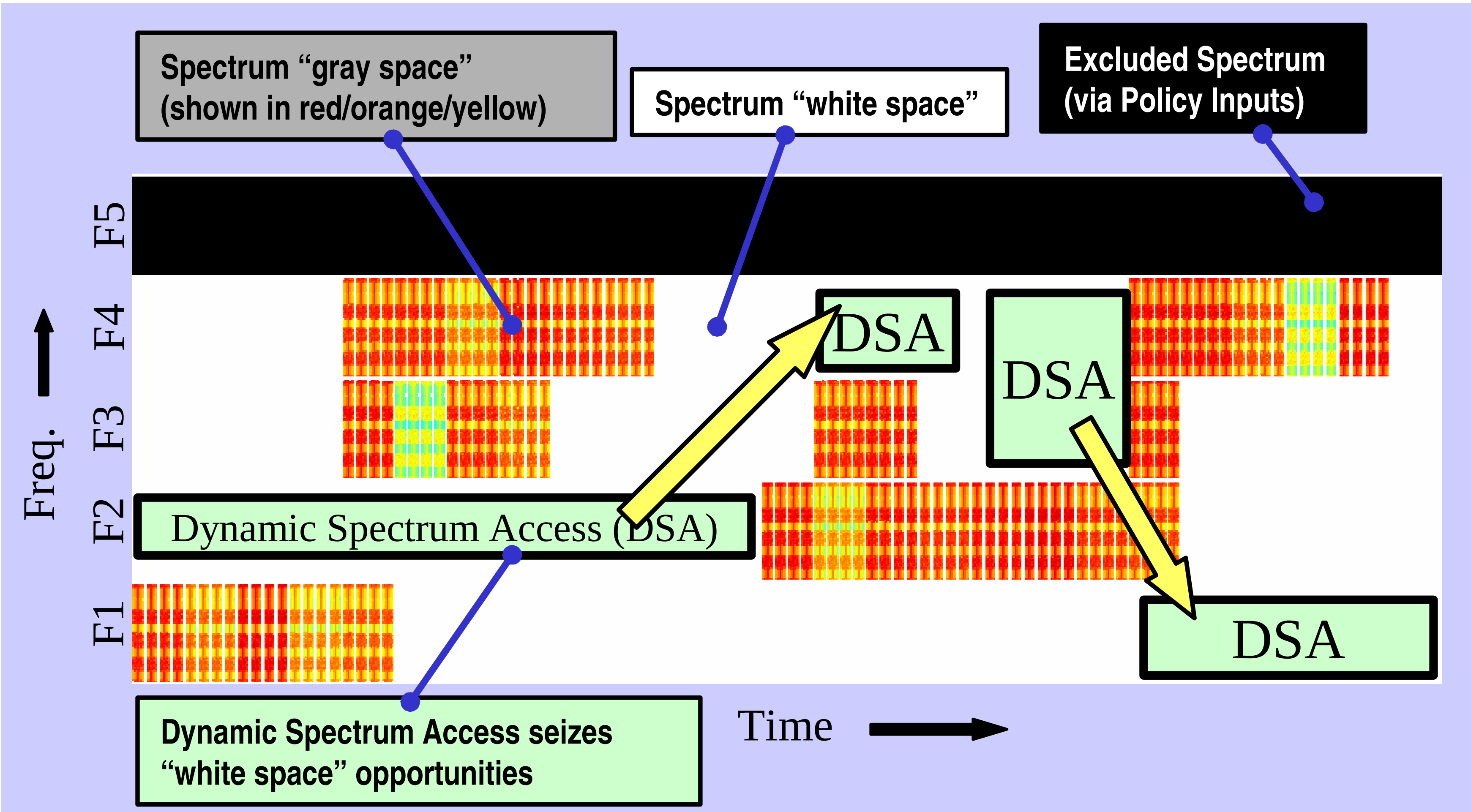

"Spectrum Hopping" solution avoids harmful interference by adapting within regulatory constraints to fill spectrum "holes"

Autonomous Dynamic Spectrum Access (ADSA) Solution Elements

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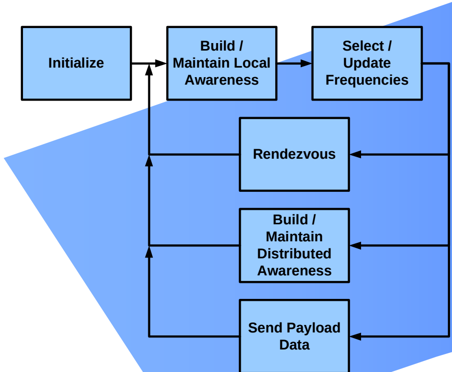
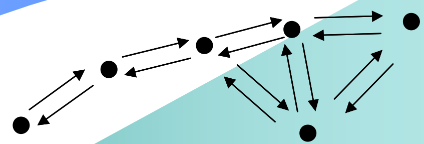
ADSA Functional Flow:

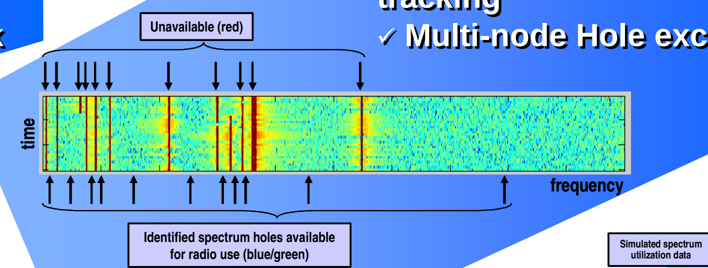


✓ Initialize and build local awareness
✓ Select initial operating frequencies
✓ Rendezvous and build distributed awareness
✓ Communicate using ADSA network

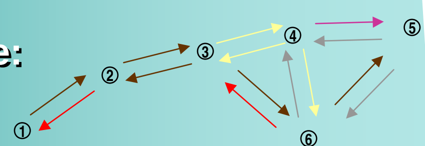


Spectrum Awareness:

✓ Continual sensing using native and wideband elements
✓ Spectrum Hole ID and tracking
✓ Multi-node Hole exchange

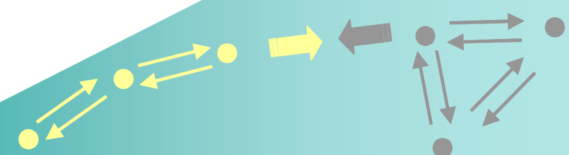


Adaptive Spectrum Use:



✓ Enables communications in fragmented spectrum
✓ Selected frequencies based on spectrum Hole ID
✓ Modified as needed for frequency-agile interference avoidance

Rendezvous:



✓ Robust network entry and re-formation in dynamic spectrum environments
✓ Combine spectrum observations with pre-determined information and external commands
✓Considers spectrum regulation and tuning range
✓ Time synch and non-time synch modes

Raytheon ADSA Technology Elements and Features

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Technology Elements:

- Adaptation algorithms, protocols and controls to enable fundamental autonomous dynamic spectrum access behaviors
- Broad set of solutions for heterogeneous mix of adaptive and non-adaptive wireless devices and network topologies
  - Enable hierarchical and peer-to-peer organization (e.g., mesh)
- Modular design and control logic that readily adapts to allow adding radio/operating system platforms, algorithms and protocols, policies, topologies and operational scenarios
  - High degree of device independence using Model Driven Architecture

Technology Features:

- Increased access to spectrum with dramatically increased utilization
- Coexistence with uncoordinated homogeneous and heterogeneous wireless networks
- Robust, stable operation via self-correcting algorithms
- Autonomous network formation and adaptation
- Interference-avoiding, policy-compliant operation
- Controlled introduction of adaptation behaviors for adjustable interference levels

Broad Raytheon solution delivers increased spectrum access for a wide range of wireless designs and system architectures

Local Spectrum Adaptation in Mesh Networks: Animation Example

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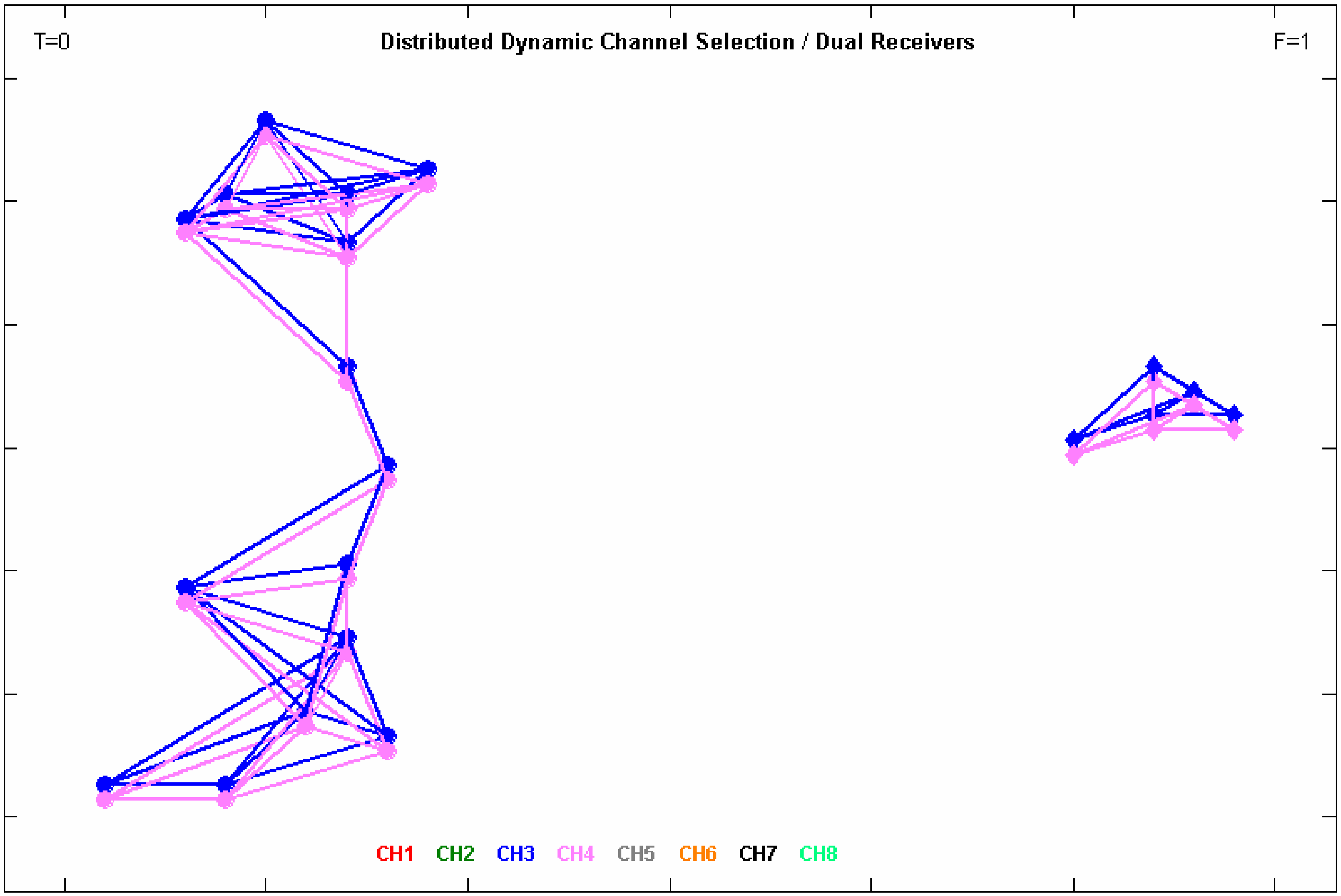
ADSA Commercial WISP | Non-ADSA Public Safety Network



Low overhead distributed adaptation algorithms enable real-time Autonomous Dynamic Spectrum Access

Autonomous Dynamic Spectrum Access: Animation Example

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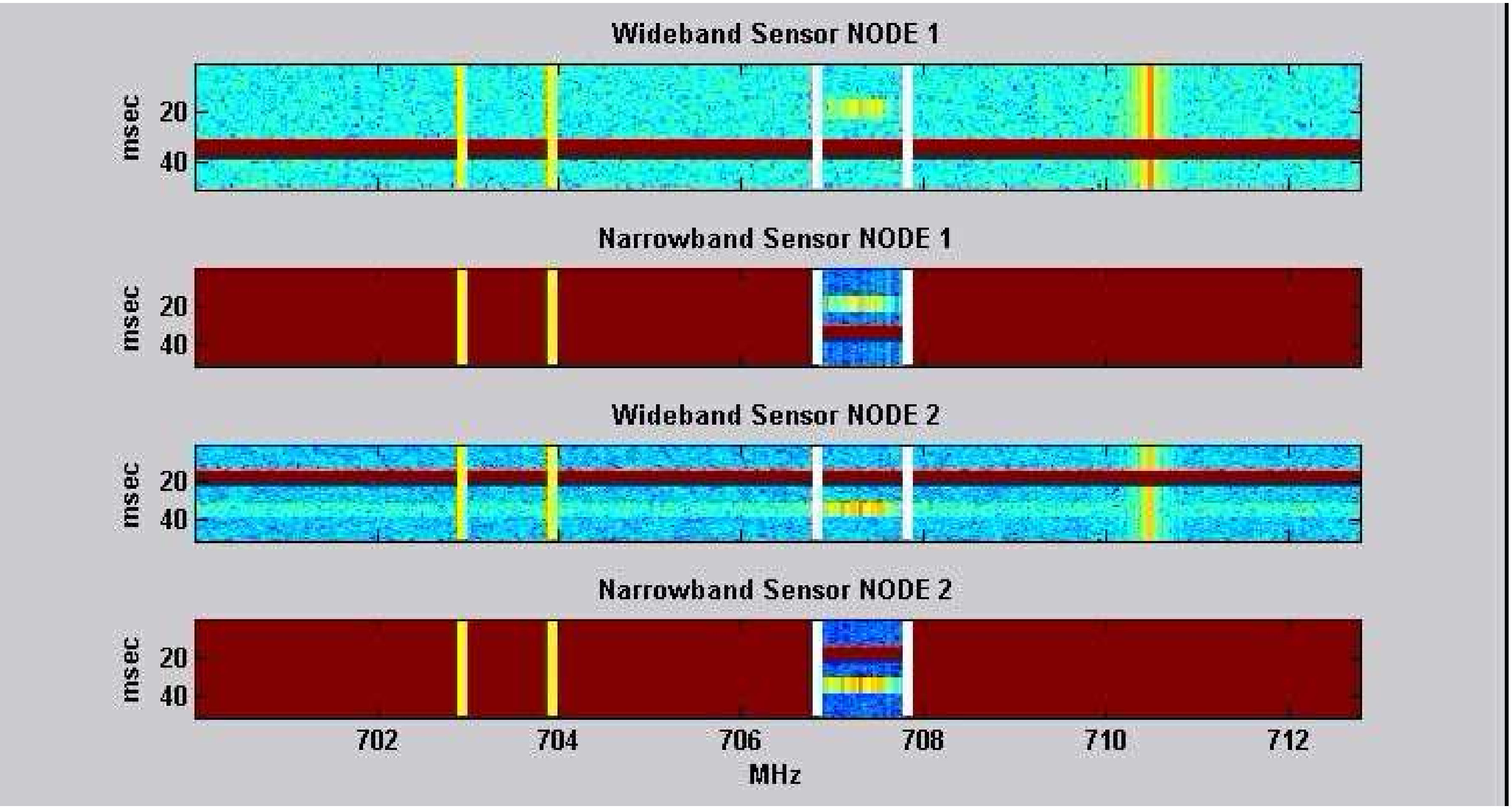

Autonomous Dynamic Spectrum Access solution facilitates coexistence by "hopping" to open spectrum

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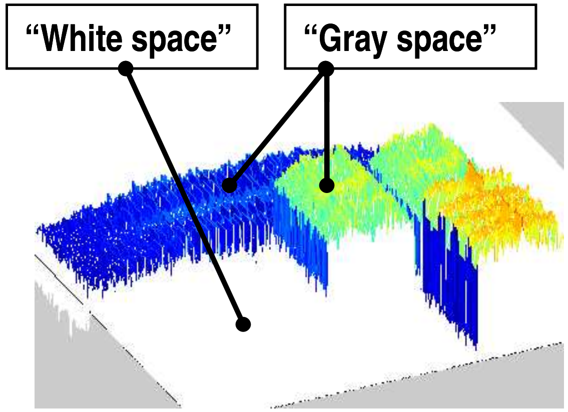
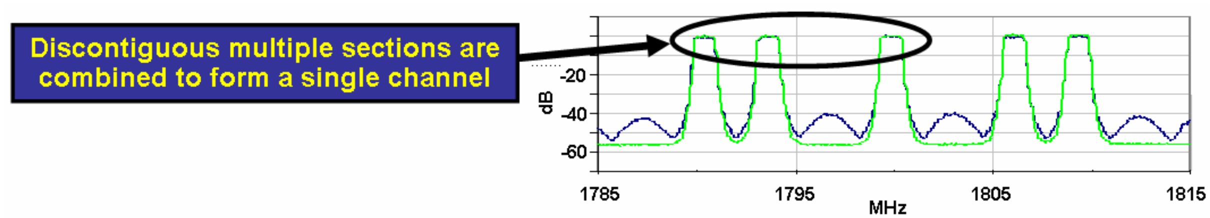
Heteromorphic Waveform



- **The Heteromorphic Waveform:**
  - **is the signal-in-space physical layer component that dynamically adapts its parameters to aggregate available spectrum opportunities into "channels" that interface with the MAC layer**
  - **transforms a set of discontiguous spectrum opportunities into a single logical spectrum use opportunity**
  - **is a single waveform that can change, by simultaneous parameter adaptation across a wide number of waveform variables**
    - ***Adaptive Radio System Driven:*** **Adaptation matches the waveform to the observed signal environment**
    - ***Heteromorphic Waveform Driven:*** **Adaptation optimizes waveform performance (e.g., BER, throughput, etc.) for the desired communications link in its operating environment (i.e., available bandwidth, traffic load, multipath, Doppler, implementation constraints, etc.)**



Heteromorphic Waveform transforms multiple discontiguous blocks of spectrum into logical channels for improved spectrum access in fragmented environments

Heteromorphic Waveform Dynamically Adapts to Match Signal Characteristics to Spectrum Opportunities

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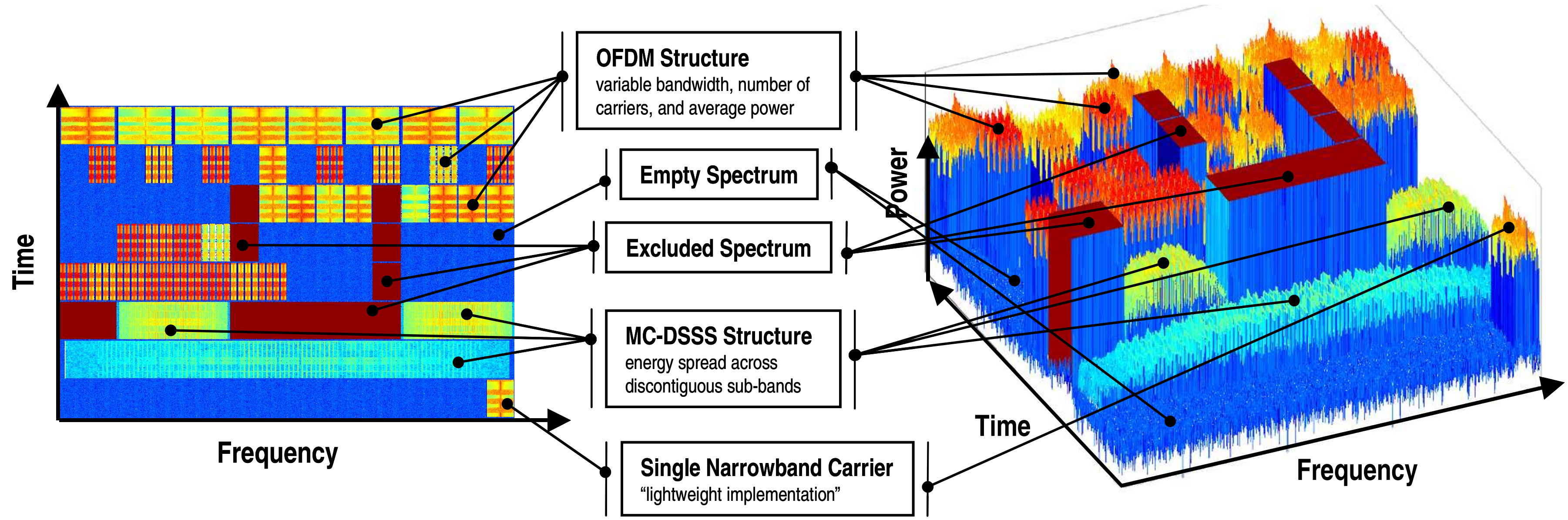

Multiple morphing techniques result in a single Heteromorphic Waveform

ADSA Network Formation and Maintenance Example

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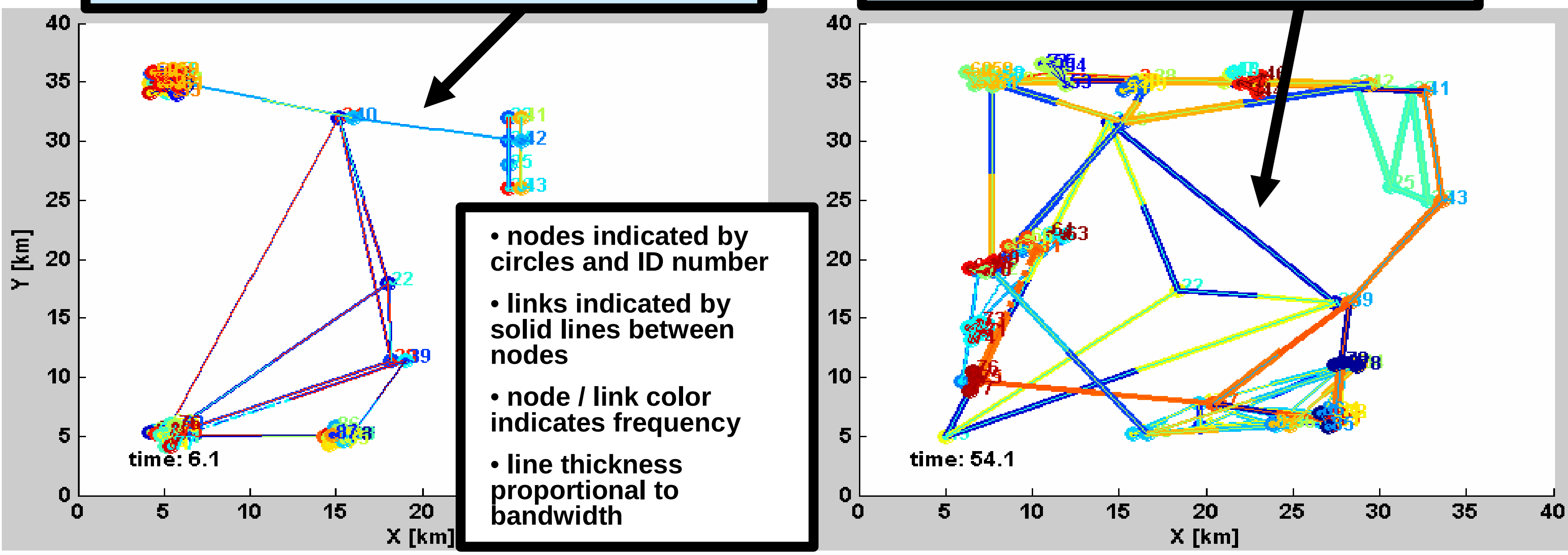
Mobile wireless Internet with mixed mesh and infrastructure connectivity

Rapid initial network formation

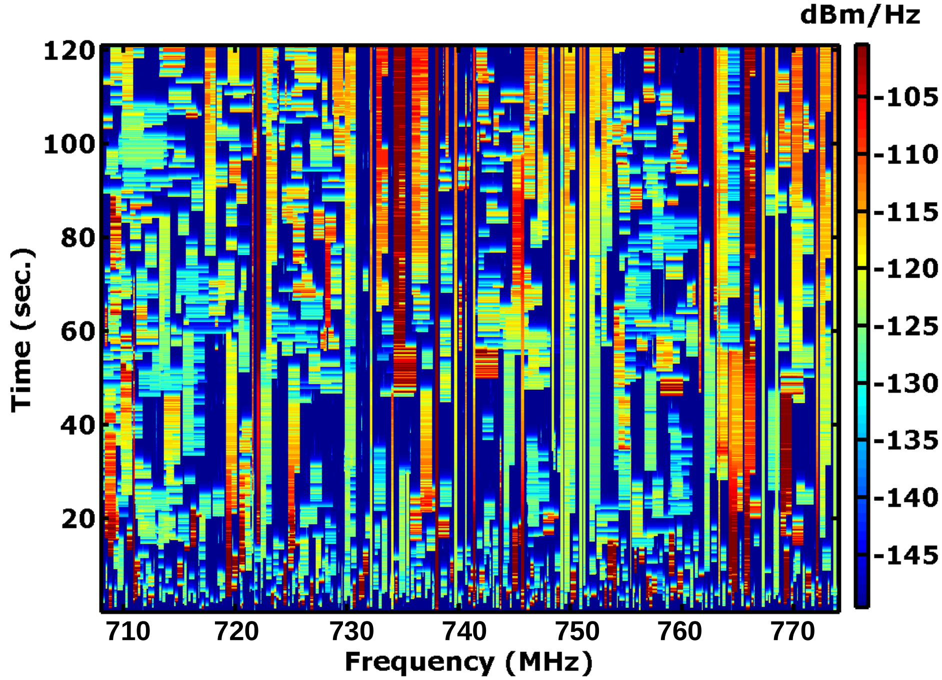
Robust network maintenance



- nodes indicated by circles and ID number
- links indicated by solid lines between nodes
- node / link color indicates frequency
- line thickness proportional to bandwidth

Reliable operation of multiple uncoordinated groups of wireless devices demonstrates robustness of autonomous dynamic spectrum access solution

ADSA Unlocks Available Spectrum



- Delivers assured communications through adaptive spectrum access in fragmented and unpredictable spectrum environments
  - Multi-frequency device operation using single channel radio hardware
  - Rapid frequency agility via coordinated Rendezvous
- Operates on a non-interfering basis by avoiding frequencies in use by other systems
  - Controls real-time broadband sensor hardware and/or internal sensing capability to establish Spectrum Awareness
- Operates within constraints specified by Policy
  - Selects operating parameters consistent within specified Policy boundaries
  - Responsive and Agile to both Policy boundary crossing and evolving regulation
- Significantly increases access to spectrum and reduces frequency planning by enabling real-time spectrum management in the wireless devices

ADSA Provides Assured and Autonomous Policy Conformance

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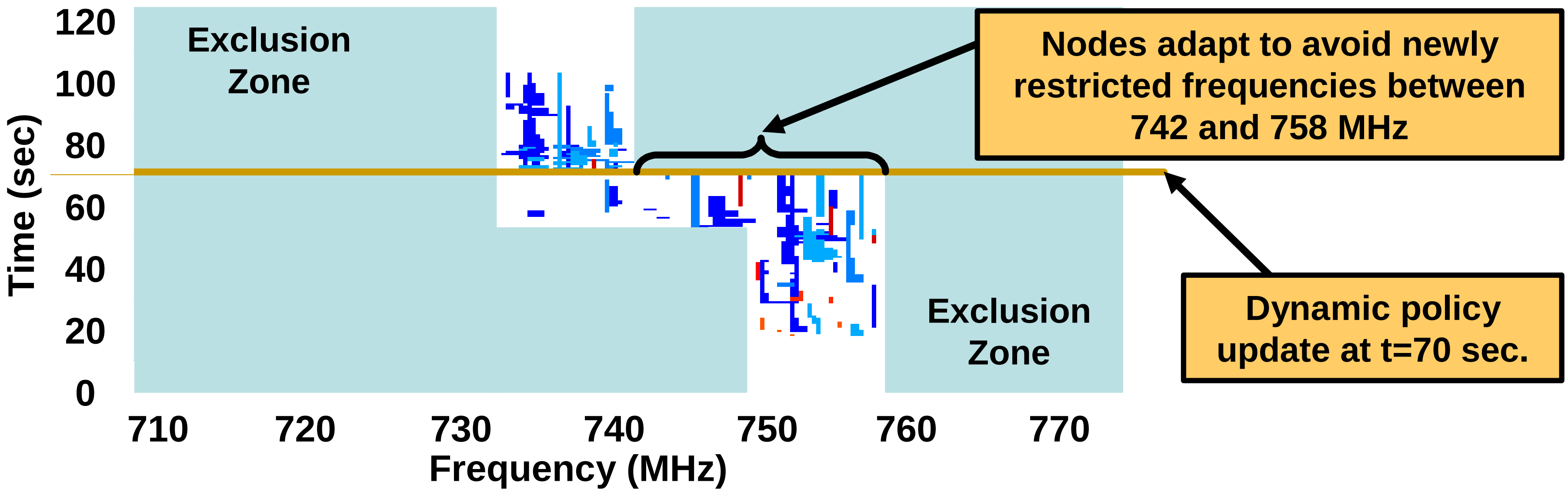
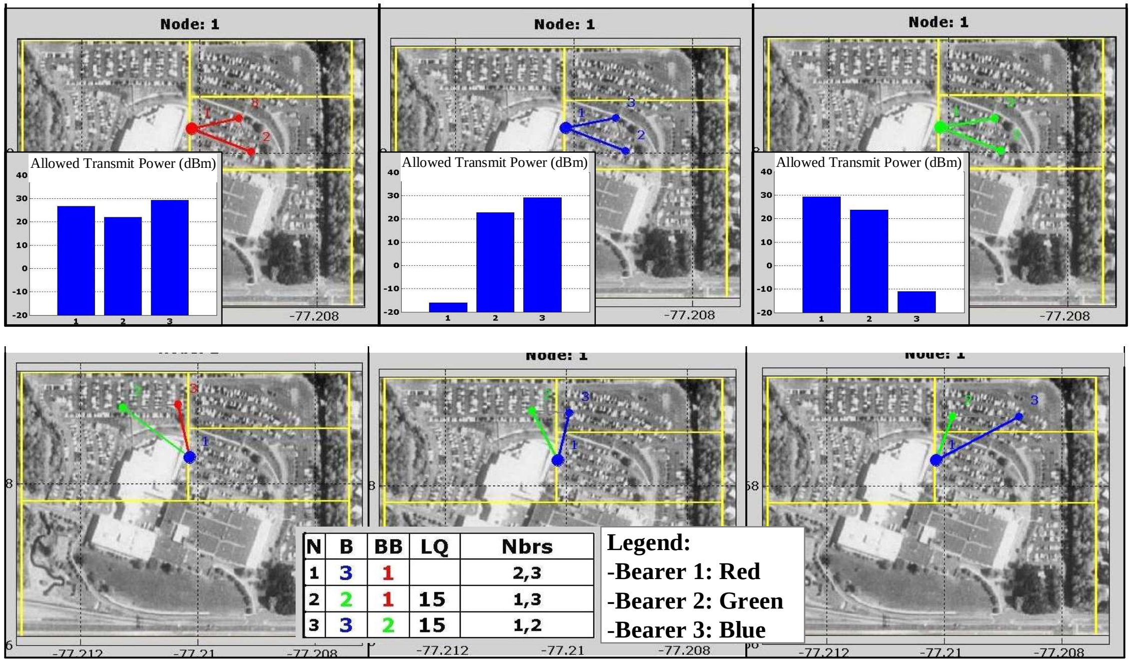


Wireless devices respond to Policy updates giving operators and regulators "shut down" capability for insurance against persistent harmful interference

ADSA-Enabled Prototype Radio Hardware Demonstration

- **Live over-the-air demonstration on Raytheon Falls Church campus (November 2004):**
  - **Distinct Raytheon and Vanu ADSA-enabled host SDR platforms**
- **Demonstrated Awareness and Adaptation Behaviors**
  - **Frequency agility and policy compliance in dynamic environments**



Successful demonstration of ADSA using prototype radio hardware validates solution viability and readiness for insertion into emerging wireless systems