# Wireless Networking Research Challenges:
## Developing & Regulating Cognition for Innovative Wireless Networking & Spectrum Access
## (or Musings on Cognition for Spectrum)

**Informational Meeting on NSF NeTS Focus Area Programmable Wireless Networking**

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**Arlington, VA**

**William D. Horne**
**The MITRE Corporation**
**703-883-6198; whorne@mitre.org**

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# Agenda

- Research Needs & Perspectives
- Programmable Radio Platforms:
  Joint Tactical Radio System (JTRS)
- Wireless Research Challenges
  - Ensuring performance for mobile networks
  - Extending “cognition” to lower network layers
  - Improving spectrum access

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# Government Research Needs: High-level Recurring Themes

- Decision Support
  - Art of decision making:  understand, improve, exploit, …
  - Collaborative:  sharing across non-traditional boundaries
  - Autonomous:  people are just another player

➔ Knowledge of the very small and the very many

- Complete Situational Awareness
  - Fewer people, shorter timelines, increased precision

➔ Anticipate not react

- Enterprise architecture/integration/modernization
  - Complexity:  requirements, technology, systems, time phasing

➔ Partnerships, coalitions, teams without boundaries

# Emerging Research Themes

- Pervasive themes:
  - Mega-systems (e.g., enterprise engineering)
  - End-to-end systems performance
  - Semantics
  - Fusion
  - Decision support/training/ cognitive systems engineering
  - Information sharing across boundaries
  - Software – It's a problem, fix it
- Key Topical Areas:
  - Biotechnology
  - Netted sensors

Implications for Wireless & Spectrum

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# Wireless Communications and Networking Research Observations

- Continues to be a “gap” between the requirements of DoD, FAA, and other government users and those of the commercial sector
- Point solutions provide minor progress toward solving hard problems
  - Interactions and unintended consequences can actually degrade the end-to-end conditions
    - More frequent “hello’s” in Mobile Ad Hoc networks: Increased overhead – decreased throughput
    - Use of TCP spoofing over SATCOM: Loss of guarantee, increased use of SATCOM resources
- Difficulty is in doing multiple hard things at once with unified solution:
  - Mobility, Intermittently connected network
  - Beyond line of sight wireless communications
  - Non-homogeneous networks and traffic
  - Security
  - Hand-held or small devices

# Challenges for Wireless Research

- Ensuring performance (QoS, etc.) and security in mobile scenarios where topology may be dynamic and variable and end-to-end connectivity may be intermittent
  - Routing and transport in dynamic topologies
  - Security
- Extending "cognition" beyond information extraction by applying to system behavior and lower network layers (e.g., physical, MAC)
  - Requires "smart", "context-aware", "cognitive" platforms typically enabled by software-defined radios (SDRs) or programmable radios
  - Requires innovative architectures & approaches
- Improving spectrum access beyond notions of interference avoidance and efficiency to areas of smart sharing
  - Spectrum scarcity due to "access" constraints, not inherent capacity limitations

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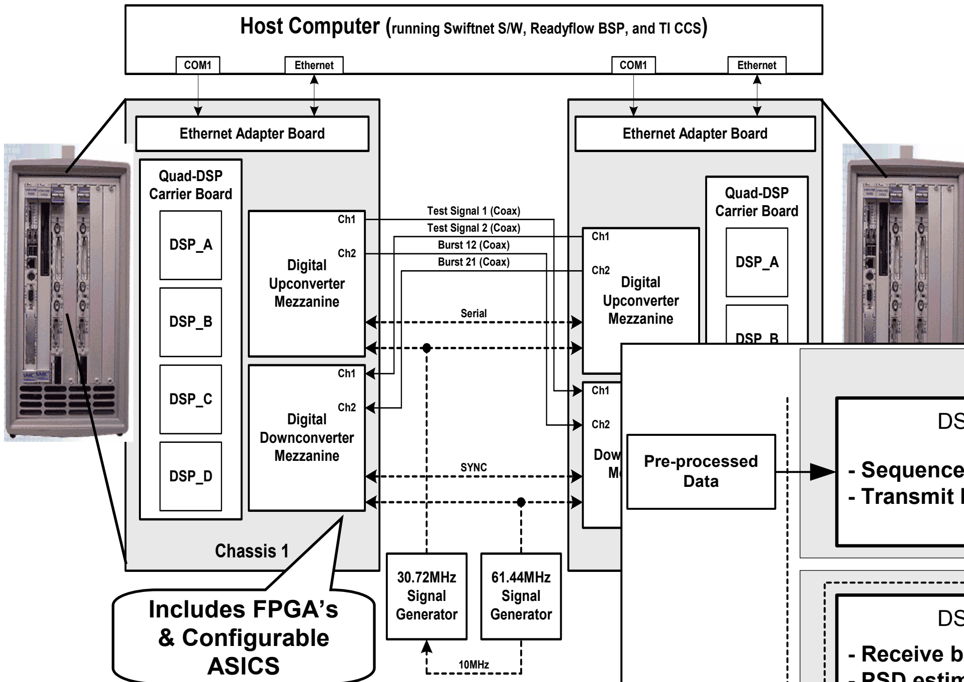
# Enabling Platforms

- Software-Defined Radios (SDRs) & Programmable Platforms
  - Programmable
  - Reconfigurable/reprogrammable
  - Flexible & Dynamic
    - Multiple waveforms & physical/MAC standards

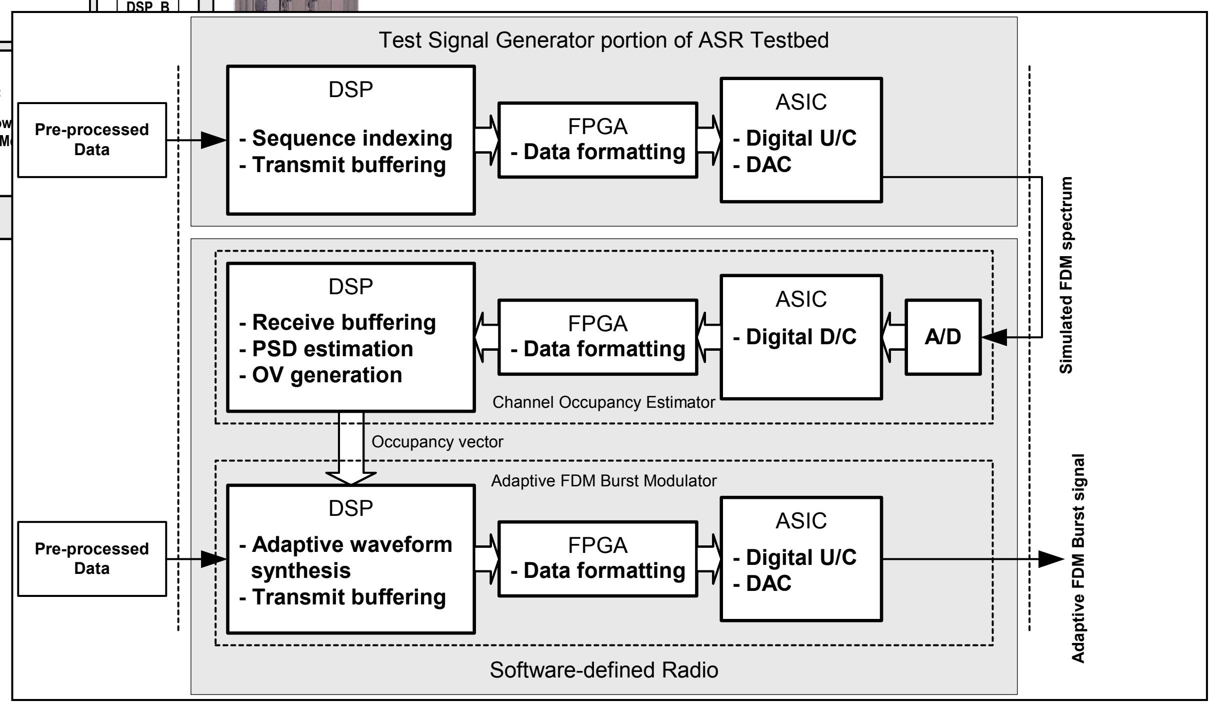
- Selected Example: Joint Tactical Radio System (JTRS)
  - Referenced by NSF NeTS Solicitation

# Radio Platform Architecture: Example
## (MITRE Adaptive Spectrum Test Bed)

- **Partitioning takes advantage of distinct programmable attributes of the ASICs, FPGAs, & DSPs**




* PENTEK Development Boards

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# Joint Tactical Radio System (JTRS)

*"The vision: Seamless real-time communications among warfighters -- through voice, data, and video -- with and across the US military services"*

- **The DoD Joint Tactical Radio System (JTRS) initiative is using a flexible approach to provide radio units that meet diverse communications while improving interoperability**
  - Software programmable radio platforms
  - Interoperability including legacy systems
  - Open architecture and extensive use of COTS and industry standards
  - Modular & Scaleable

**Family of radios (2 MHz – 2 GHz)**
- Service requirements are "clustered" so that similar requirements can be met with a single acquisition effort

**Common Architecture and Open Standards** (Software Communications Architecture)
&
**Common Waveforms**

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# JTRS Clusters: Platforms

- **Family of radios (platforms) -> Service requirements are "clustered" so that similar requirements can be met with a single acquisition effort and platform**

**Cluster 1 (Ground Vehicular, Rotary Wing, TACP) (Army Lead)**

**Cluster 2 (Handheld MBITR JTRS) (USSOCOM Lead)**

**Airborne, Maritime, Fixed-Site (AMF) JTRS** (formerly Clusters 3&4)
(Air Force/Navy Lead)

**Cluster 5 (Embedded, Handheld, Manpack) (Army Lead)**

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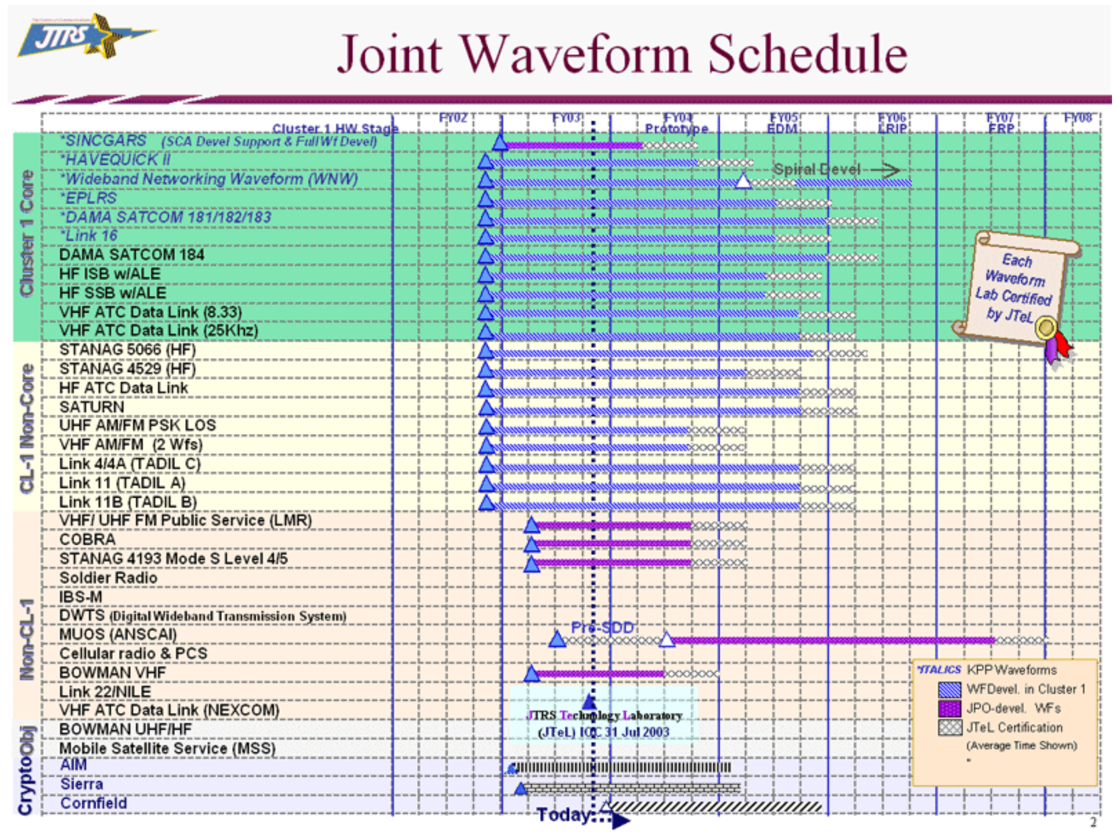
# JTRS Waveforms

- A "waveform" is all of the functionality between the RF input/output (antenna) and the user interface
  - Software-based
- JTRS is developing:
  - Legacy waveforms (for interoperability)
  - New military waveforms (Wideband Networking Waveform (WNW))
  - Commercial and public safety

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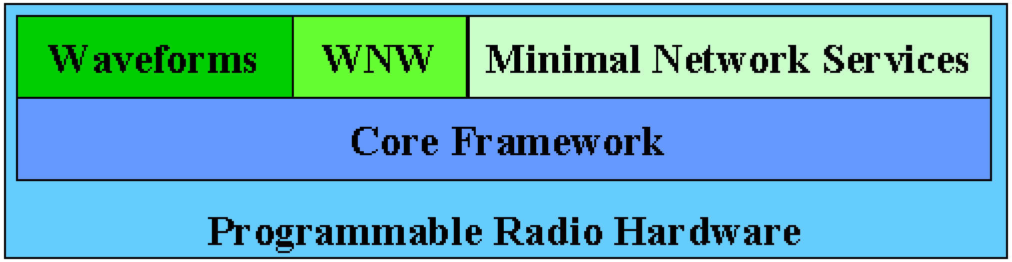
# Software Communications Architecture (SCA)

- The SCA is an open architecture framework:
  - Hardware (HW) Framework
  - Software specification for waveform applications
  - Core Framework (standard operating environment)
    - Standard interfaces that allow waveform applications to run on multiple hardware sets
- SCA enables:
  - Porting of waveforms across radio platforms
  - Interoperability among radios
  - Use/reuse of common software across waveforms
  - Scalability
  - COTS (potentially)

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# Software Communications Architecture (SCA) (cont.)

- SCA represents
  - Software Defined Radio Forum (SDR Forum) endorsed SCA
  - Object Management Group (OMG) considering SCA as international standard

# Challenges for Wireless Research

- **Ensuring performance (QoS, etc.) and security in mobile scenarios where topology may be dynamic and variable and end-to-end connectivity may be intermittent**
  - **Routing and transport in dynamic topologies**
  - **Security**
- Extending "cognition" beyond information extraction by applying to system behavior and lower network layers
  - Requires "smart", "context-aware", typically enabled by software-define programmable radios
  - Requires innovative architectures &
- Improving spectrum access beyond notions of interference avoidance and efficiency to areas of smart sharing
  - Spectrum scarcity due to "access" constraints, not inherent capacity limitations

**Extensive Research Space !**

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# Research Perspectives: General

- Successful implementation of Mobile ad hoc networks involves challenges in:
  - Mobility management
    - Pure ad hoc networking operation where nodes are free to move in any direction at any speed
    - Clustered ad hoc networking operation where nodes are clustered in groups where members of the cluster carry a specific mission (e.g., military networks)
    - Level of self-organization depends on the network considered -> Self-organization is implemented in the routing and MAC design
  - Medium access control (MAC) and routing protocols
    - MAC protocol plays a key role in ensuring efficient access and utilization of spectrum resources and overall system throughput
    - Routing in ad hoc networks supports network scaling up to hundreds of nodes
      - The challenge is that all nodes are mobile
      - Rate of link failure can be high if mobility is high
  - Security, Authentication, etc.
  - Power control
  - Quality of Service (QoS)
    - QoS-based routing protocols
    - Resource reservation schemes and MAC protocols

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# Research Perspectives: Examples

- Power saving techniques that reduce energy consumption without significantly diminishing the capacity or connectivity of mobile ad hoc network
  - Energy-efficient MAC and routing protocols for topology maintenance)
- Adaptive network routing and media access algorithms where decisions can be based on the conditions of the physical layer (such as location, spectrum availability, terrain data, power consumption, etc.)
- Analysis and development of inter-layer interactions/integration, including physical and higher layers, that improve throughput for mobile ad hoc networks
  - Adaptive MAC to make efficient use of spectrum resources not productively utilized
- Impact of directional communications on design of routing protocols and medium access techniques for ad hoc networks
  - Development of algorithms to take advantage of directional/electronically steered antennas to increase system capacity on high-band links
- QoS-based solutions for routing, resource reservation, and MAC in ad hoc networks
  - Control messages and system resources required to achieve a desired QoS and impact on network load
- Improved analytic methods and modeling for performance evaluation of ad hoc networks including spectrum utilization
- Solutions to problems in tactical wireless networks that can lead to a node-centric characterization and improve connectivity and reliability of the ad hoc network:
  - Topological instability, Link unreliability, and changing bandwidth

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# Challenges for Wireless Research

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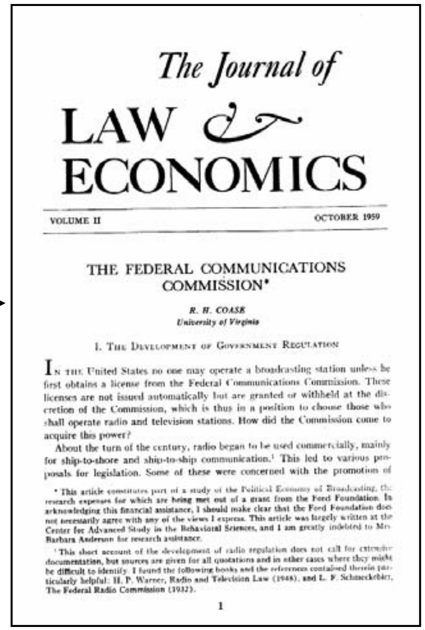
# Spectrum Policy Receptive to "New" Ideas

Radio "chaos"



The Journal of

LAW & ECONOMICS

VOLUME II — OCTOBER 1959

THE FEDERAL COMMUNICATIONS COMMISSION*

*R. H. COASE*
*University of Virginia*

I. The Development of Government Regulation

In the United States no one may operate a broadcasting station unless he first obtains a license from the Federal Communications Commission. These licenses are not issued automatically but are granted or withheld at the discretion of the Commission, which is thus in a position to choose those who shall operate radio and television stations. How did the Commission come to acquire this power?

About the turn of the century, radio began to be used commercially, mainly for ship-to-shore and ship-to-ship communication.[1] This led to various proposals for legislation. Some of these were concerned with the promotion of

* This article constitutes part of a study of the Political Economy of Broadcasting, the research expenses for which are being met out of a grant from the Ford Foundation. In acknowledging this financial assistance, I should make clear that the Ford Foundation does not necessarily agree with any of the views I express. This article was largely written at the Center for Advanced Study in the Behavioral Sciences, and I am greatly indebted to Mrs. Barbara Anderson for research assistance.

[1] This short account of the development of radio regulation does not call for extensive documentation, but sources are given for all quotations and in other cases where they might be difficult to identify. I found the following books and the references contained therein particularly helpful: H. P. Warner, Radio and Television Law (1948), and L. F. Schmeckebier, The Federal Radio Commission (1932).

1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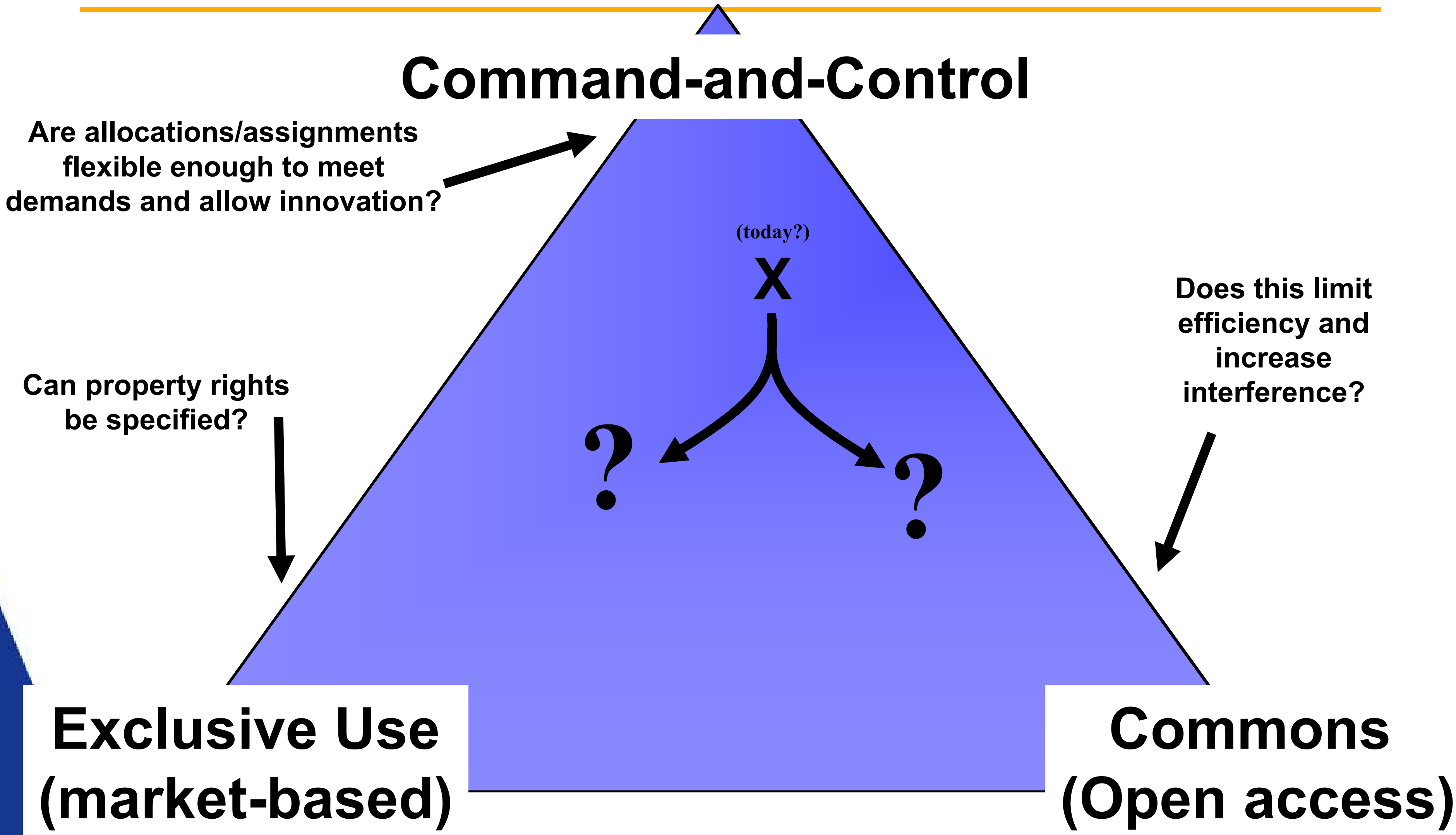
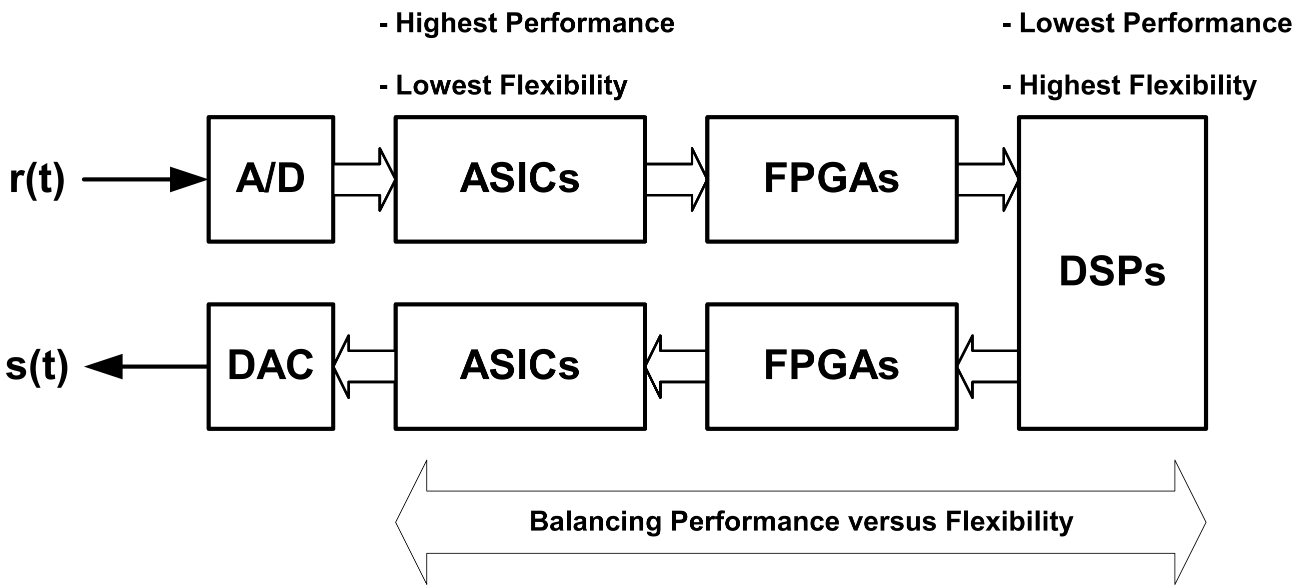
# Spectrum Models



# Technology Advances Enable Cognition

- Advances in technology are increasing the capability to "cognitively" access the spectrum across all of its dimensions in the spectrum space
  - Digital signal processing-based radios provide the platform for these dynamic radio systems
  - However, a variety of technologies contribute to the increasing capability




Example SDR Architecture and System Trade-offs

# The Spectrum Space

- **The Spectrum Space is a multi-dimensional space that is difficult to define.**

| General Class | Parameter | Units | Notes |
|---|---|---|---|
| Power | Power (or field strength) | W (or V/m) | Often viewed as the independent variable of the spectrum space |
| Frequency | Frequency | Hz | |
| Time | Time | sec | |
| Space | Location | latitude, longitude, elevation | 3 dimensions (can be generalized to other reference systems besides geocentric) |
| | Signal direction (transmission direction, angle of arrival) | azimuth, elevation | 2 dimensions (note: perspective is important whether from transmitter or receiver) |
| Signal | Polarization | vertical/horizontal (clockwise/counter-clockwise) | |
| | Coding/modulation | (variable) | not necessarily orthogonal |

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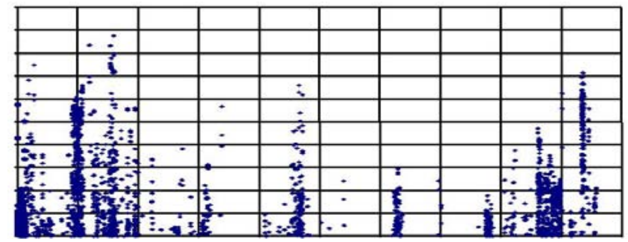
# Adaptive Spectrum Operations Concept (Non-cooperative environment)

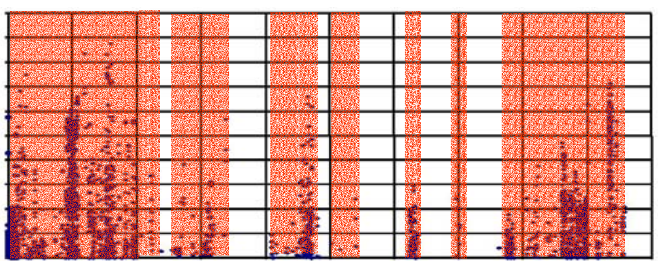
Spectrum utilization varies over the dimensions of spectrum (time, frequency, space, etc.)



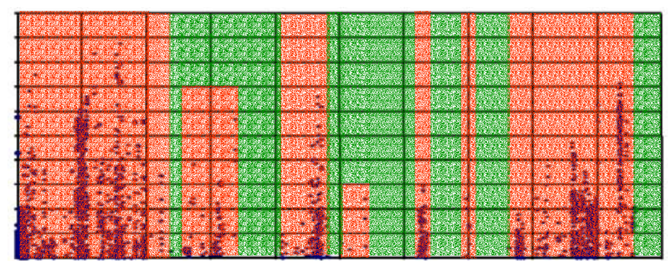
Radio Frequency (MHz)

**Step 1** Determine which channels are busy

**Step 2** Create waveform(s) to use idle spectrum



Radio Frequency (MHz)



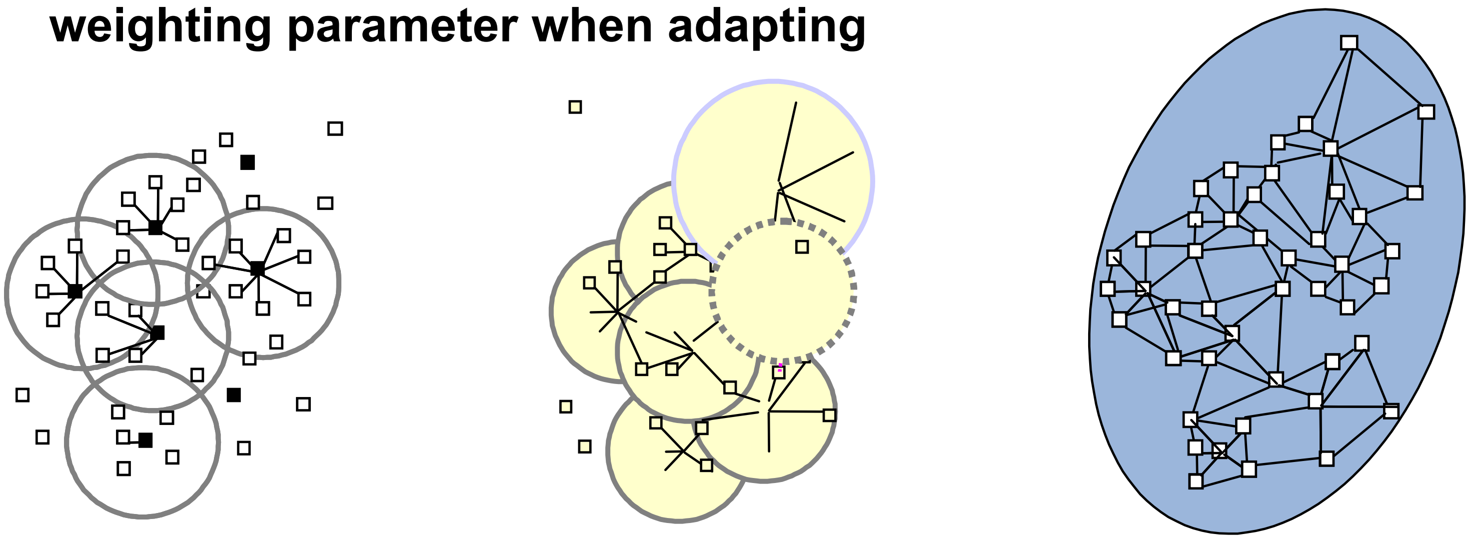
Radio Frequency (MHz)

**Waveform adaptable to variable, non-contiguous spectrum**

**Step 3** Repeat steps 1 & 2 to monitor spectrum and adapt when environment changes

# Adaptive Spectrum Operations Concept (Cooperative environment)

- Unlike opportunistic approaches, sharing information can greatly improve spectrum access utilization
  - Beacons: information provided to known or unknown entities
  - Networking: client/server and ad hoc
- Wireless networking
  - As network topology evolves, routing and other aspects adapt
  - Routing algorithms need to fully considered spectrum access as weighting parameter when adapting



Ad hoc wireless network topology (clustering, layers, flat)

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# Cognitive Spectrum Architectures

To Be Defined

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# Challenges for Wireless Research

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# What is Cognition?

***Cognition n. 1. The mental process or faculty by which knowledge is acquired. 2. That which comes to be know, as through perception, reasoning, or intuition; knowledge.*** [1]

- **Definition of cognitive radio**
  - **Mitola[2]: knowledge based construct**
    - "The term cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to:

      (a) detect user communications needs as a function of use context, and

      (b) to provide radio resources and wireless services most appropriate to those needs."
  - **FCC NPRM - no real definition but states:**
    - **"These technologies include, among other things, the ability of devices to determine their location, sense spectrum use by neighboring devices, change frequency, adjust output power, and even alter output waveforms."**

1. The American Heritage Dictionary of the English Language
2. J. Mitola, *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio,* Dissertation, KTH, June 2000

# What is Cognition? (cont.)

- Key attributes:
  - Awareness/knowledge: environment/situation/location/etc.
  - Ability to act: reaction/negotiate/etiquette/etc.
- Examples
  - Dynamic Frequency Selection (DFS)/ “Listen-before-talk”
  - Dynamic/adaptive spectrum access
    - Sense the radio frequency environment or link performance
    - Synthesize its waveform autonomously & opportunistically
    - Adjust multiple parameters within the spectrum space
    - Operating in cooperative networked systems and/or environments with non-cooperating systems
- References/Regulation from outside communications (“civil society constructs) may help find ways to “regulate” cognition

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# Cognitive Radio Activities

- **Dynamic Frequency Selection (DFS) . . . Limited "cognition"**

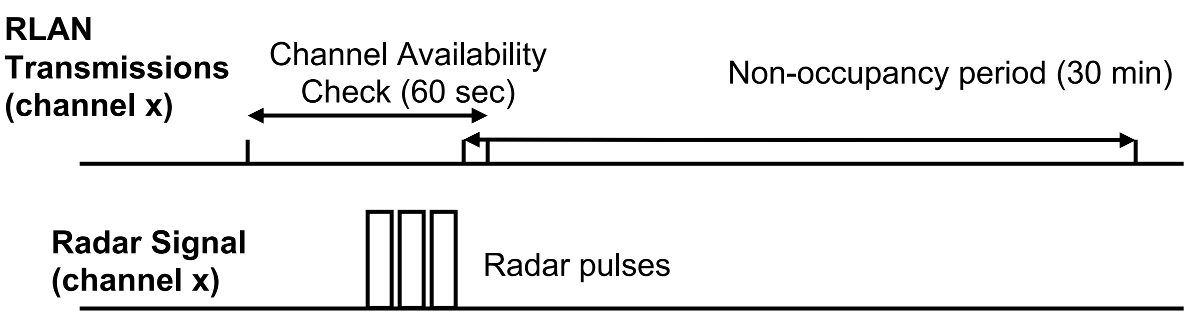
- **Policy Review . . .**
  - **FCC Initiatives (e.g., Cognitive Radio NOI/NPRM)**

- **DoD/Industry/Academia has a variety of "cognitive" projects**
  - **JTRS/WNW**
  - **DARPA's neXt Generation (XG) Program**
  - **Academia including NSF's recent awards**
  - **Many others can be classified as "cognitive"**
    - **MITRE's Adaptive Spectrum Radio**

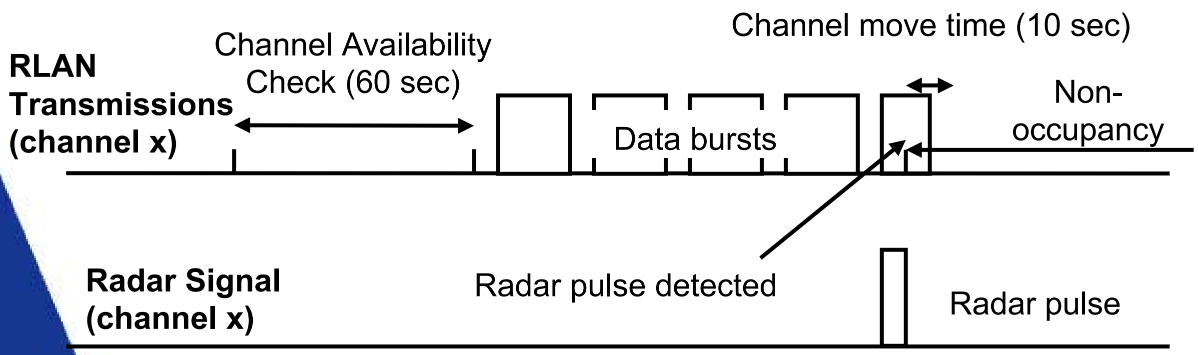
# Dynamic Frequency Selection (DFS)

- **DFS is a mechanism built into wireless systems to allow sharing of the 5 GHz bands between wireless local area networks and radar systems**
  - **Automated "listen before talk"**
  - **Limited adaptation (change channel or cease transmission)**

**Case 1) RLAN Detects Radar Signal on Channel x Prior to Operations**




**Case 2) RLAN Detects Radar Signal on Channel x After Data**




| Parameter | Value |
|---|---|
| DFS Detection Threshold | –62 dBm e.i.r.p. of < 200 mW,<br>–64 dBm e.i.r.p. of > 200 mW to 1 W avg. over 1 μs |
| Channel Availability Check Time | 60 sec |
| Non-occupancy Period | 30 min |
| Channel Move Time | ≤ 10 sec |

# “Cognition” = Behavior?

- Adaptation is one of the overarching attributes of “cognitive” systems whether such change is provided by:
  - Exploiting environmental conditions (opportunistic)
  - Using system-wide knowledge (networking)
  - Measuring and maintaining link quality
- Capturing this overarching attribute of “cognitive” systems with *behaviors* may assist both system designers and policy makers
  - Interoperability and coexistence
  - Defines key aspects for requirements definition or regulation
- Key considerations for behavior-based approaches:
  - Flexibility: set technical parameters balancing needs of existing system with ability to introduce new technology
  - Cost: reliance on detailed compliance testing and monitoring needs to be weighed with the increased cost
  - Security: knowledge of system behaviors may unduly compromise the secure operation of systems
- Are there other/complementary ways to “regulate” “cognition” beyond defining “behaviors”?

# Possible Behavior Constructs

| High-Level Behavior (external) | Mechanism/Parameter | Considerations |
| --- | --- | --- |
| **Prohibited** | Limit access through defined spectrum space regions (frequency band, time, location, directionality, etc.) | May be used to protect existing systems during introduction of adaptive systems or for protecting critical systems |
| **Causal (if-then)** | Given location in the spectrum space (e.g., physical location and frequency), access may be permitted with specific constraints | May require mandated existence and availability of databases |
| | Given measured environment, access may be permitted with specific constraints | - Requires system to measure environment and react accordingly (e.g., DFS)<br>- May also include limits based on the overall environment (e.g., "interference temperature") |
| | Given signal identification, access may be permitted with specific constraints | Use of both databases and measured environment to determine actions |
| **Interactive (negotiated or shared control)** | Negotiated access using spectrum space dimensions (e.g., request access to x band during y timeframe in location z) | - Such behavior enables regulatory constructs like secondary markets<br>- Less interactive mechanisms, such as beacons, can also be used to define access |
| **Dynamic** | Automatically determine what criteria and actions are needed based on measurements, shared information, and requirements (e.g., interference levels) | Enables innovative concepts based on dynamic system needs and conditions |

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# Observations/Lesson about "Cognition" (so far . . .)

- Adaptive/"cognitive" capabilities are essentially fundamental to improving spectrum utilization regardless of the underlying model (command & control, commons, or exclusive use)
- Policy needs to be agnostic to underlying implementations and algorithms
- Protocol/network negotiation limits adaptability and potential gains in spectrum utilization—RF awareness not likely to limit
- Policy questions from behavior-based view include:
  - Can more extensive behaviors, such as interactive mechanisms requiring negotiations, be defined rather than reactive mechanisms?
  - Can a set of well-defined, high-level behaviors be defined that can be used for defining appropriate "cognitive" functions?

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# "Cognition" Research Perspectives

- How regulate/certify/etc.?
  - What flexibility allowed? Does defining behavior and associated parameters require limitations to flexibility?
    - How implement secondary markets or similar dynamic mechanisms?
  - How define "domain aware" (regulatory, facility, etc.) systems?
    - Example: Airplane access point from takeoff to landing
  - How test/certify "automated" systems (e.g., external measurements, internal governors, etc.)?
- What mechanisms to insert policy to radios?
  - Database (externally distributed, internally derived, etc.)
  - Control channels
  - Protocols—what and at what layers? (more than just physical)
    - "Semantic" data (e.g., XML (JTRS using), future advances (XG))
- What other aspects need to be considered?
  - Security
  - Standards

# Cognitive Wireless & Spectrum Architectures

- **Programmable platforms emerging . . .**
- **Demand for wireless connectivity and access for variety of needs . . .**
- **Policy & regulatory community ready . . .**

**Architectures To Be Defined**

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