Towards Policy-Defined Cognitive Radio

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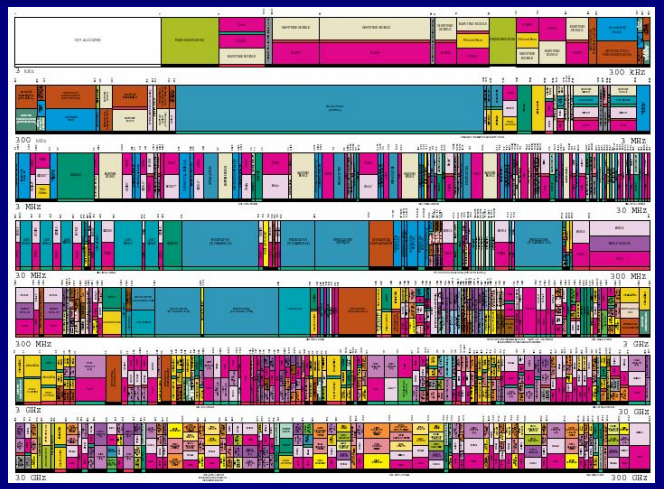
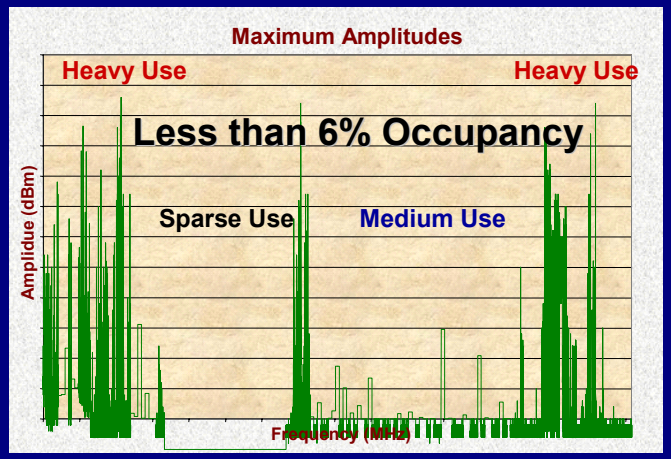
What is XG?

- neXt Generation Communications
- Basic idea: Opportunistic spectrum access
  - sense the spectrum you want to transmit in
  - look for “holes” or “opportunities” in time and frequency
  - transmit so that you don’t interfere with the licensees
- Key Challenges
  - wideband sensing, opportunity identification, coordinating spectrum use in a network setting
  - transitioning to a new regulatory policy framework, traceability, verification and accreditation

Why XG?

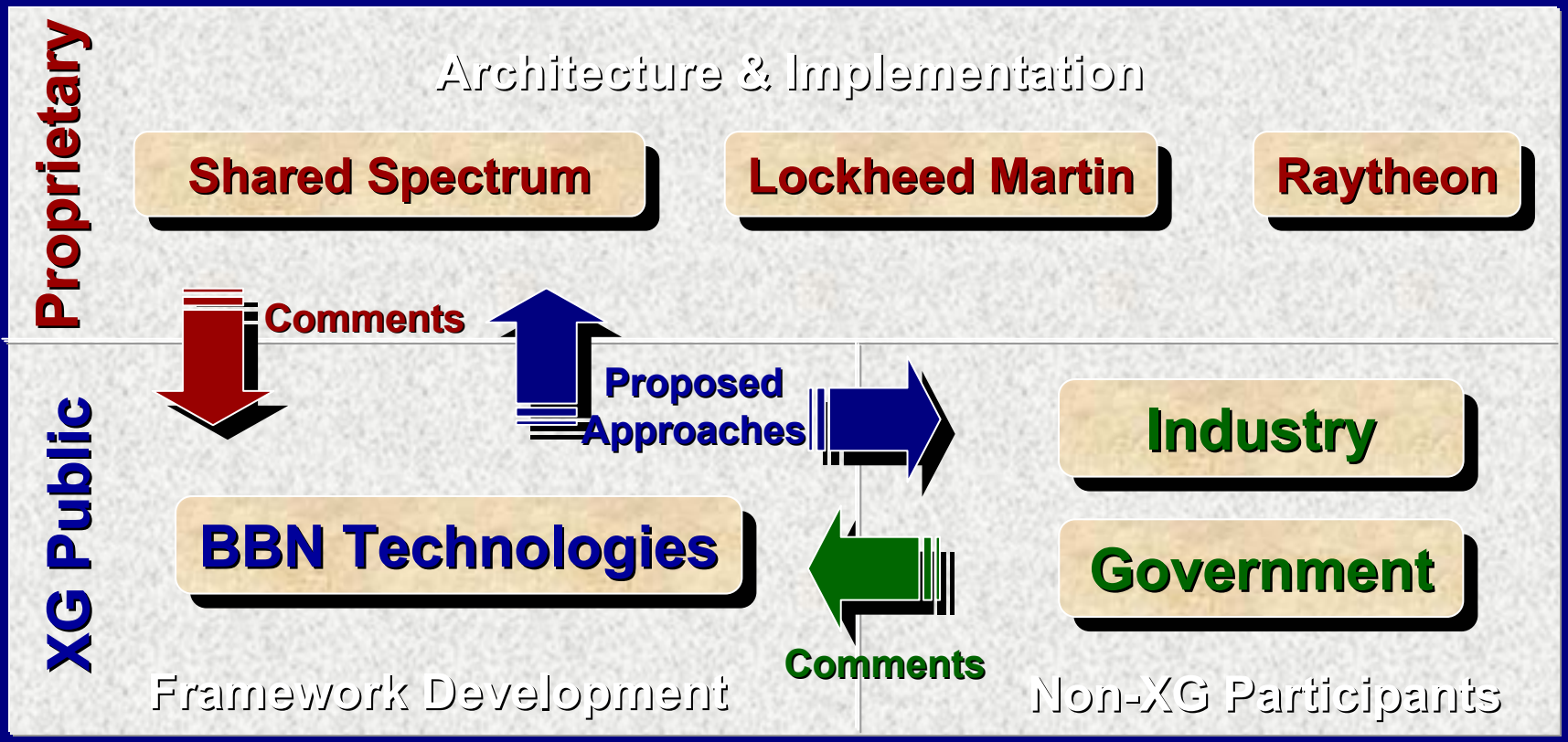
- Current "static" spectrum allocation strategy is wasteful
  - huge opportunities exist in time, frequency, and space
  - <u>apparent</u> spectrum scarcity
- Deployment difficulty
  - allocating spectrum for overseas military operations
  - using Wi-Fi network overseas
- Spectrum policy is evolving
  - Spectrum Policy Task Force report
  - recent FCC notices



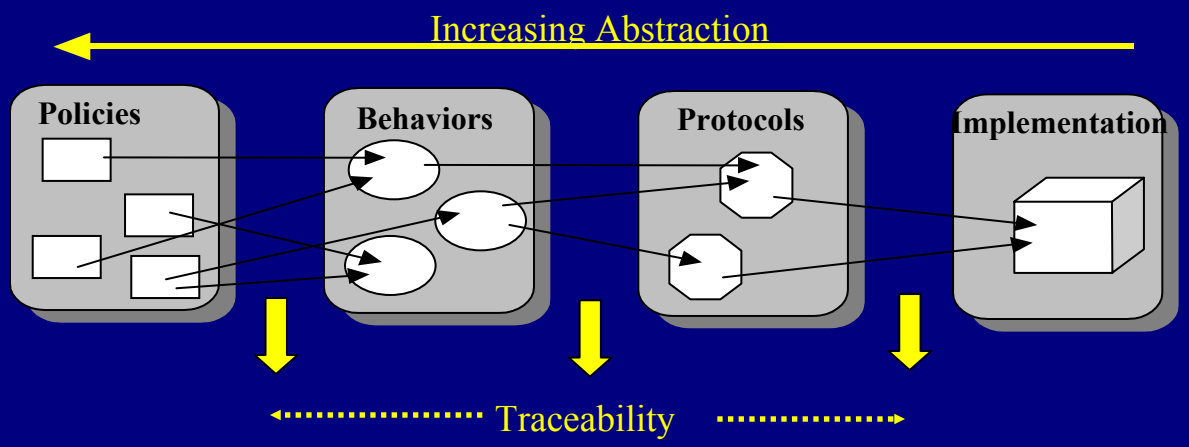


BBN's Role in XG

BBN is developing an XG Framework with the objectives of ensuring longevity, easing regulatory approval, and enabling industry participation



BBN's XG Approach



- Decouple policy, behavior, protocol, and implementation
  - provide traceability from policy to emission behavior (ease V V & A)
- Enable policy-driven opportunistic sharing of spectrum
  - develop a policy language framework for XG (focus of this talk)
  - identify policy-defined XG behaviors that are configurable in-situ
  - develop protocols and interfaces for XG systems

Policy-Defined Cognitive Radio

Our Long Term Vision For XG

Dynamic Policy Awareness:
Regulatory and System Policy

Environment Awareness:
Spectral Occupancy
Location, Time, Neighbors

Policy-Defined Cognitive Radio

Self-Awareness:
Spectrum Sensing,
Adaptive Control of Frequency, Power, Waveform, Beamform

Adapt Radio Behavior Based Upon Awareness

(In Order To Opportunistically Exploit Available Spectrum)

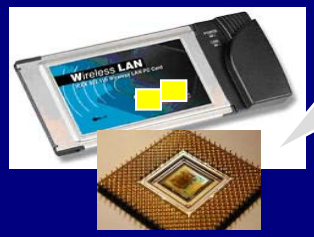
Eventually Optimize Radio Behavior Based Upon Awareness Subject to Policy Constraints

Dynamic Software-Based Policies

Technology Push For Machine Readable Policy

FCC Rule Book

Hardwired policy

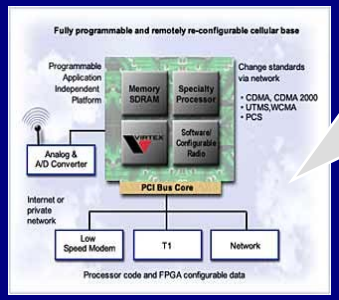


Limited or no field programmability (e.g. ASICs)

Canned behaviors: few/fixed modes of operation

Machine-Readable Policies

Software-based policy



Highly programmable, fast, low power devices (e.g. FPGAs)

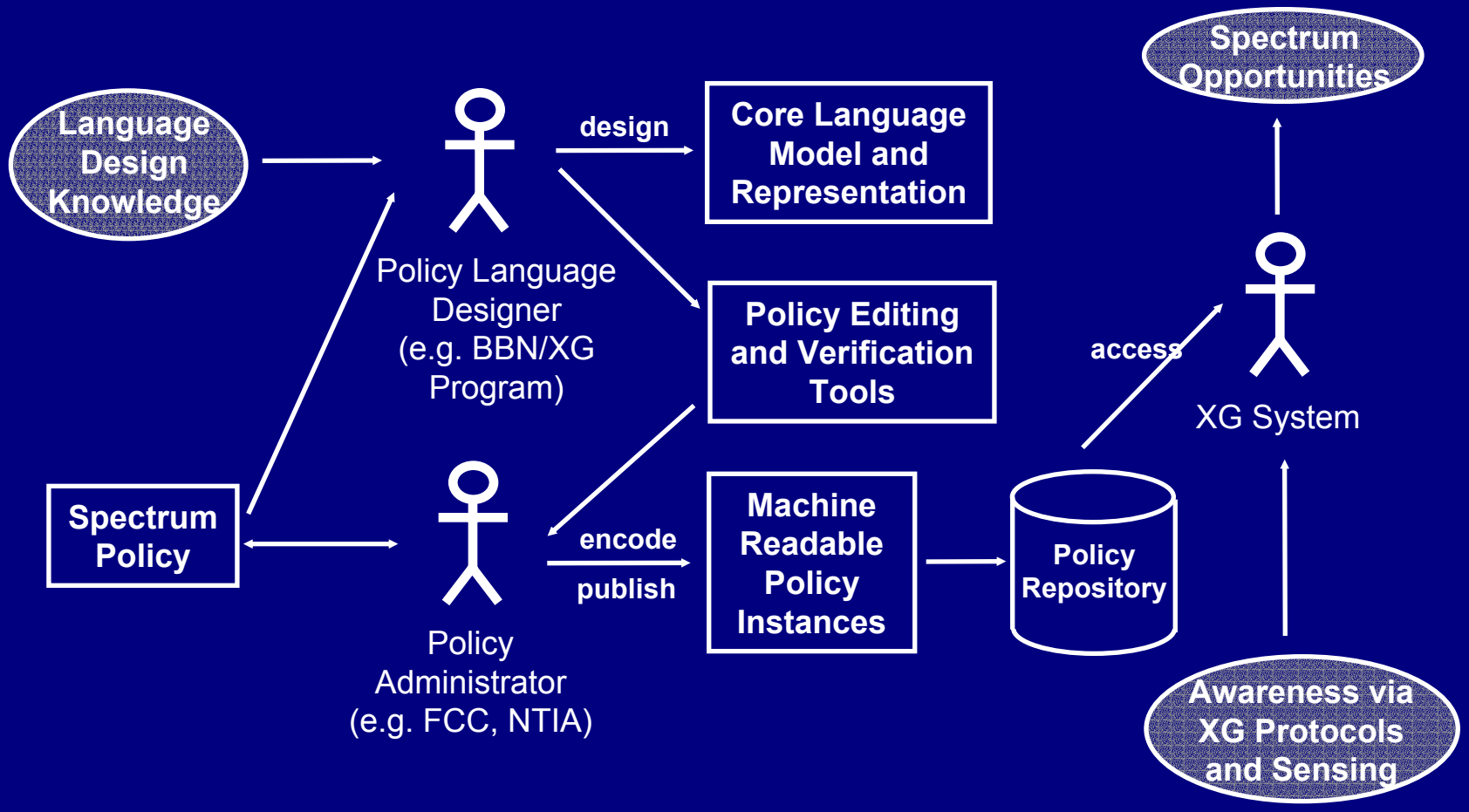
Agile behaviors: numerous modes of operation, not just legacy modes

Software based policies are *necessary* to <u>exploit</u> the emerging agility of devices and allow in-situ policy-based <u>control</u> of radio behaviors

Benefits of Machine Readable Policies

- Adaptation to policies changing over time
  - allows development of technology in advance of policies
- Adaptation to policies changing over geography
  - e.g., use a new smart card when in a new country
- Secondary spectrum markets
  - let primary user to develop sub-policies for secondary users
- Self-checking policies
  - implications of policy interactions worked out in advance
- Potentially speed up deployment
  - eliminate need to accredit per device configuration per country

XG Policy Language Framework



Spectrum Policy Language Design

Leverages Knowledge Engineering and Semantic Web

Design Policy Language Model in UML

Tools: UML tools such as ArgoUML or Rational Rose

Export to DAML ontology

Tools: DAML export tools such as DUET Plugin for ArgoUML/Rational Rose or UML2DAML for TogetherJ

Enrich language e.g., add XML Schema datatypes for signal parameters

Tools: XML/text editors

Iterative Refinement

Create example policy instances

Tools: human readable surface syntax (CLIPS), Protégé-2000 with DAML+OIL Plugin, or DAML/RDF/XML/text editors

Validate ontology and instances

Tools: DAML tools such as DAMLvalidator, or other based on Jena API

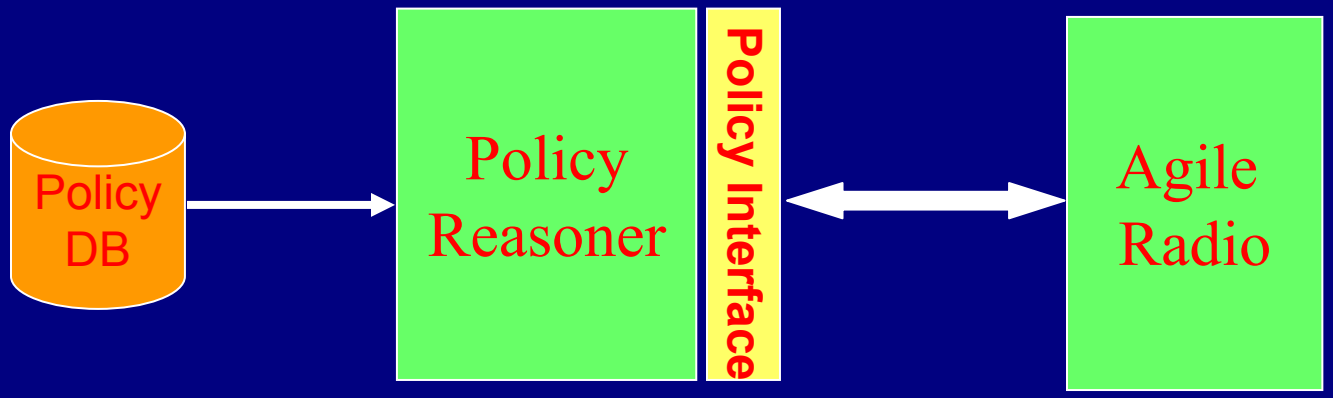
Policy Processing

Tools: Production rule systems such as CLIPS/Jess, cwm, Euler, Java Theorem Prover

Legend: currently being used by our group (will change as we transition to OWL)

Policy Reasoner and Interface

Making Policy Information Accessible to the Device



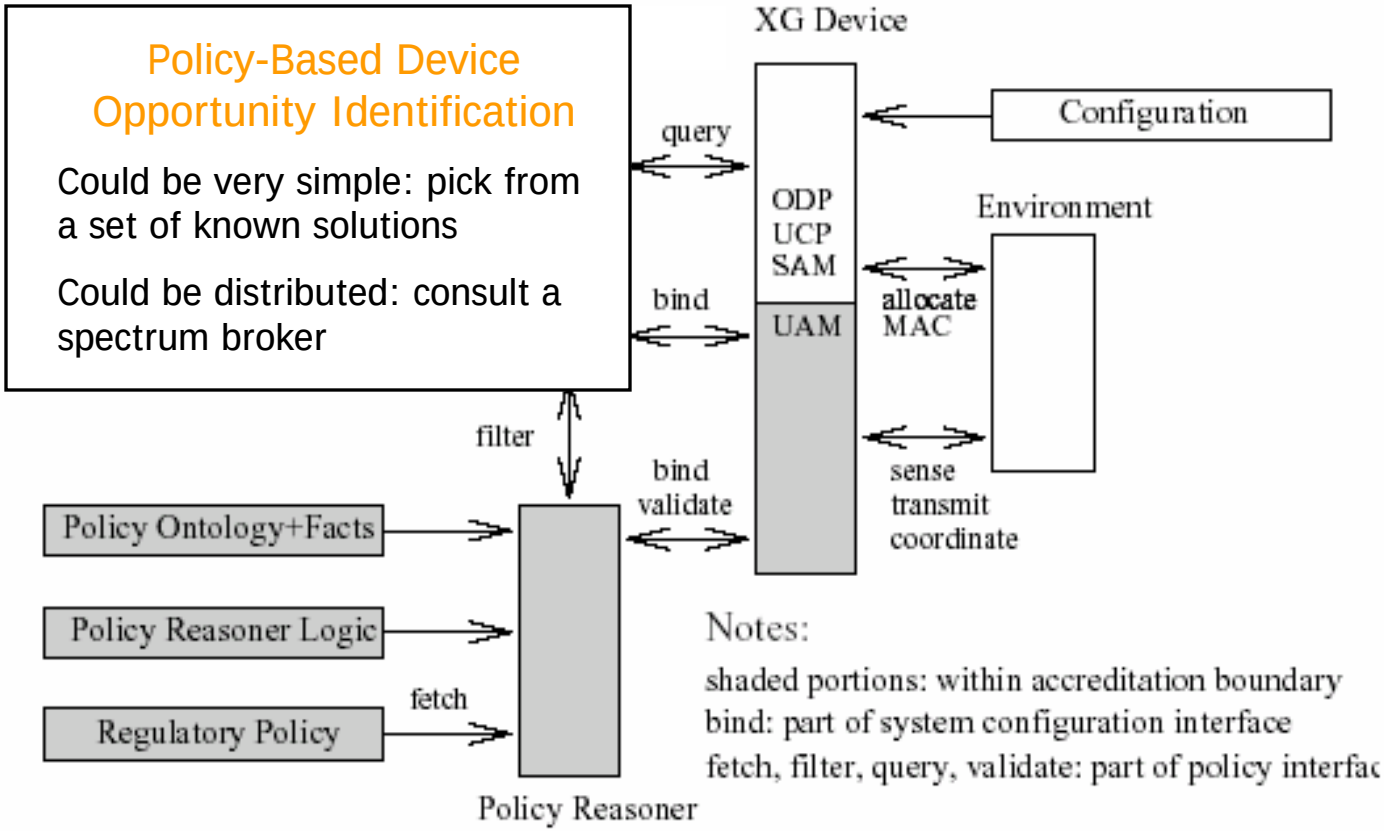
- Extract relevant policies from a (huge) repository
  - based on device type and intended operating environment
- Interpret and reason about policies based on
  - current state of the system and its environment
  - infer valid opportunities and permitted emission behaviors
- Assert/prove emission behavior conforms to policy

Policy Reasoner and Interface

Regulatory Policy and Accreditation Issues

- Regulatory policy does not tell device what to do
  - only specifies what constitutes valid use of spectrum
    - we feel a declarative/rule-based approach works best here
  - ideally describes spectrum opportunity in a general manner
    - not tied to a particular protocol, device, waveform, or mode
- System policy need not have the same restrictions
  - can be as simple or as complex as vendor chooses
    - procedures, rules with procedural attachments, or constraint logic programming
- Need a clearly demarcated accreditation boundary
  - ideally what lies within should be device independent
  - keep device dependent tradeoffs and optimizations outside

Our Policy Reasoner Architecture



Policy Reasoner Architecture

Design Notes: Practical Issues

- Inside accreditation boundary
  - device independent conformance validation
  - accredited device parameters and methods
- Outside accreditation boundary
  - policy-based device opportunity identification
    - involves system dependent tradeoffs and optimizations
  - most XG protocol innovations and systems software
- Conformance validator device independent: reusable
  - avoid m×n problem for accreditation
    - m: policy sets, n: device configurations
    - m+n+1: verify reasoner (1), validate each policy set (m), accredited parameters and methods once per device (n)

Policy Reasoner Architecture

Design Notes: Complexity Issues

- Existence of valid opportunity an NP-complete decision
- Given fully qualified opportunity (all parameters bound), we can check validity in polynomial time
  - plug in and evaluate Boolean expression (caveat: disjunctions)
    - bind device parameters, invoke device methods as needed
- Finding best opportunities for a device is NP-Hard
  - search and prune combinatorial decision space
  - however, fast system dependent optimizations are possible
    - known solutions and heuristic searches that work for the device
- Enumerating all fully qualified opportunities intractable
  - also, cannot prune opportunities in system-neutral fashion

Summary

- XG paves the way for Policy-defined Cognitive Radio Networking
  - harnesses agility of reconfigurable radios within a policy framework
    - take both regulatory intent and situational awareness into account
  - other innovations and novel system concepts I did not talk about today
    - abstract behaviors, protocols, interfaces, policy language, ontologies etc.

- What are the hard problems?
  - cognitive optimization of device operation under policy constraints
    - reasoning in real time for dynamic beamform and waveform composition
    - efficient search and prune of combinatorial decision space
  - building agile solutions that are also robust and interference avoiding
  - checking policy implications for device performance in advance
  - clever protocols to identify, disseminate, and use opportunities
    - bootstrapping coordination channels and neighbor discovery (not too hard)

Combining disparate EE and CS domains is the key to success here!

Thank You

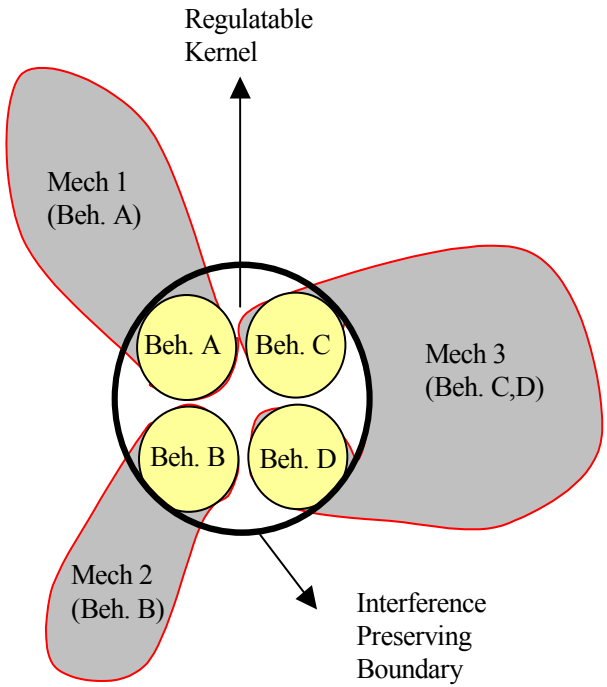
For more information, please see:

http://www.darpa.mil/ato/programs/XG
http://www.ir.bbn.com/projects/xmac/working-group

Defining XG: Abstract Behaviors

- Abstractions that hide details of implementations
- Specify a "core" set of policy-defined abstract behaviors
  - core of interest to regulators
  - allow innovation outside
  - much like trusted security kernel
- Interference preserving boundary
  - inside the boundary is a "regulatable kernel" that should be of interest to regulators
- We are not specifying protocols

Core Behaviors Form a "Regulatable Kernel"



Abstract Behaviors Summary

- XG abstract behaviors include:
  - two internal behavior classes
    - Spectrum Awareness Management (XG-SAM)
    - Usage Accounting Management (XG-UAM)
  - two protocol behavior classes
    - Opportunity Dissemination Protocol (XG-ODP)
    - Use Coordination Protocol (XG-UCP)
  - seven interfaces
    - sensing, transceiver, control channel, policy, XG-to-MAC, allocation, and system capabilities
- Together they are a minimum useful set that enables
  - opportunistic spectrum sharing, policy-centric operation, traceability

XG Evaluation Platform using OPNET

- XEP is a simulation model of MAC-level protocols, and physical layer abstractions
  - serves as a model of notional (simple) XG device
  - allows experimentation using a mix-and-match of various mechanisms for opportunity identification, dissemination, and use
  - policy interface allows policy controlled behaviors

Policy Language Requirements

- Must handle complexity of current spectrum policy
  - a patchwork that evolved over time
  - written for human (engineer/lawyer) interpretation
- Must be extensible, and preferably standards-based
- Must support a logical framework for
  - validation of completeness and consistency of policies
  - verification of policy-conformant usage

DARPA Agent Markup Language
(DAML)

- DAML is a markup language that builds upon:
  - XML technology
  - knowledge representation research
- Provides more structure than XML DTDs/Schemas/RDF
  - passes semantic model (and syntactic model) along with data
  - traditionally, semantic model is not machine-readable
    - instead, agreed upon by designers a priori (in paper or verbally)
      - ends up deeply embedded in different application implementations
- Based on a formal logic model (Description Logics)
  - enables deductive inference

Why DAML for XG Policy Language?

- DAML has the right set of features, for example:
  - reification (make statements about statements)
    - e.g. a policy rule governing when XG policy rules will apply
  - inheritance and extension
    - e.g. rules for TV bands inherit/extend from broadcast bands
  - ontology, inference and theorem proving support
- Being standardized as OWL by the W3 Consortium
  - combines US (DAML) and EU (OIL) efforts
  - considerable government investment in this area
- Some insights from prior use of DAML-based policy