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Policy-Cognitive Opportunistic Communications

Two Problem Domains That Require A Robust High-Performance Knowledge-Base

Rajesh Krishnan

krash@bbn.com

BBN Technologies

10 Moulton Street, Cambridge, Massachusetts 02138, USA

DARPA/NSF Workshop on Real-Time Knowledge Processing For Wireless Network Communications
Stanford University, Palo Alto, CA
March 29, 2006

This work was supported in part by the DARPA Advanced Technology Office under the XG and DTN programs.

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Introduction

- Policy Cognitive Opportunistic Communications
  - programmability enables new communications paradigms
    - software radio, active networks, composable protocols, network overlays, agents, semantic web
  - enable communications whenever there exist opportunities
    - not just under common case optimization assumptions
  - trusted management plane to support cognitive networks
    - reasoner software infrastructure suitable for networking
  - explicitly declare policy rather than procedurally specify strategy
    - resource trade-offs and mission requirements change
      - let the network reason which protocol strategies will satisfy the policy
- Problem domains requiring a high performance knowledge base:
  - opportunistic spectrum access
  - opportunistic data networking for disruption tolerance

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Opportunistic Spectrum Access

DARPA neXt Generation Communications (XG)

- Virtually all usable spectrum is allocated, but very little of it is actually being used at any given time and place
  - huge opportunities for reuse exist if enabled by policy
- The basic idea is simple
  - sense the spectrum you want to transmit in
    - wideband sensing and signal characterization
  - look for opportunities in time and frequency and exploit them
    - radios with spectrum and waveform agility, spectrum sharing etiquettes
- But there's a catch
  - just because spectrum is unused does not imply re-use rights
    - transmit, but do no harm (cause no interference) to incumbents
      - e.g., radio astronomy users, public safety users, and spectrum lessees
  - complex patchwork of rules varying with band and regulatory agency

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Dynamic Policy Awareness

Technology Push For Policy Agility

FCC Rule Book

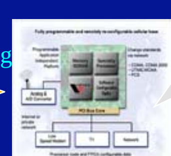
Hardwired policy

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

Canned behaviors: few/fixed modes of operation

Machine-Understandable Policies

Dynamic policy loading



Highly programmable and versatile devices (e.g., DSPs, SDRs)

Agile behaviors: numerous modes of operation, not just legacy modes, multi-national operation

A language framework to express policies in machine-understandable form is necessary in order to control and exploit radios with spectrum agility

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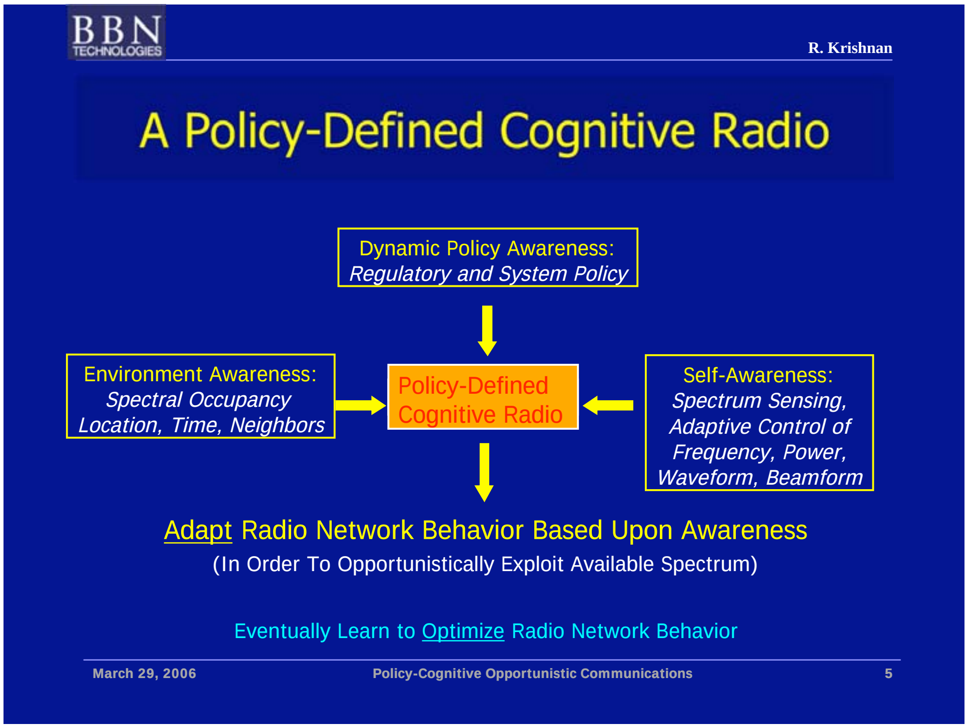
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A Policy-Defined Cognitive Radio
Dynamic Policy Awareness: Regulatory and System Policy
Environment Awareness: Spectral Occupancy Location, Time, Neighbors
Policy-Defined Cognitive Radio
Self-Awareness: Spectrum Sensing, Adaptive Control of Frequency, Power, Waveform, Beamform
Adapt Radio Network Behavior Based Upon Awareness
(In Order To Opportunistically Exploit Available Spectrum)
Eventually Learn to Optimize Radio Network Behavior
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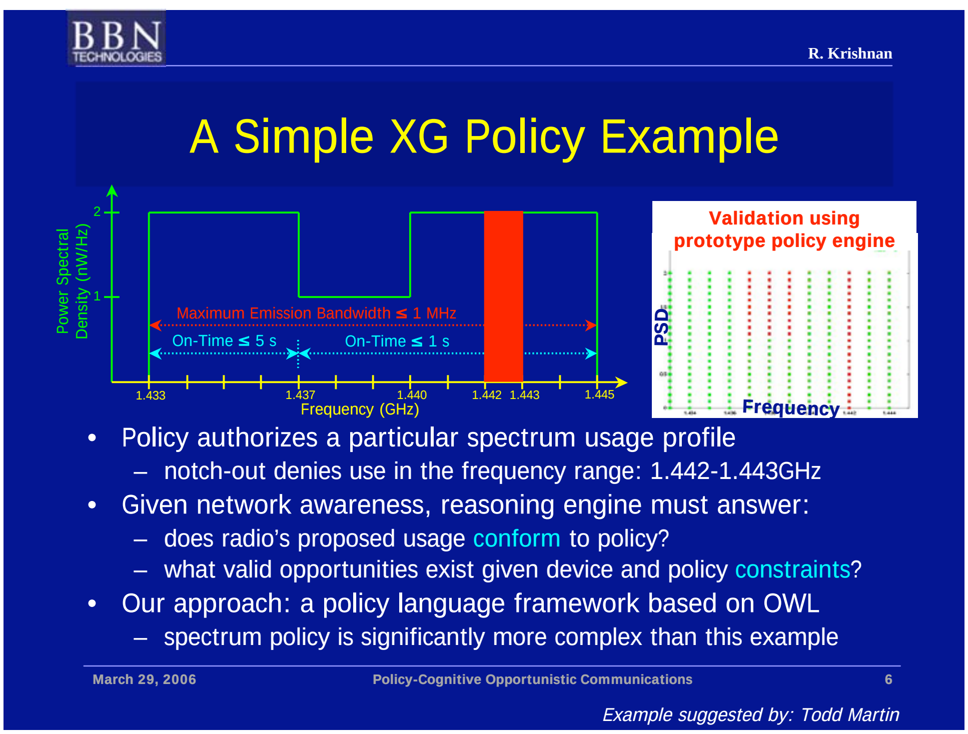
5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A Simple XG Policy Example
Power Spectral Density (nW/Hz)
2
1
Maximum Emission Bandwidth ≤ 1 MHz
On-Time ≤ 5 s
On-Time ≤ 1 s
1.433
1.437
1.440
1.442
1.443
1.445
Frequency (GHz)
Validation using prototype policy engine
PSD
Frequency
• Policy authorizes a particular spectrum usage profile
– notch-out denies use in the frequency range: 1.442-1.443GHz
• Given network awareness, reasoning engine must answer:
– does radio's proposed usage conform to policy?
– what valid opportunities exist given device and policy constraints?
• Our approach: a policy language framework based on OWL
– spectrum policy is significantly more complex than this example
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6
Example suggested by: Todd Martin

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Opportunistic Data Networking

DARPA Disruption Tolerant Networking (DTN)

- Continuous end-to-end connectivity cannot always be guaranteed
  - challenged networks: high mobility, interplanetary delays, adversarial attacks, acoustic links, lack of infrastructure, failure, misconfiguration
  - traditional networking optimized based on path stability assumptions
- Yet, communications can occur provided there is no permanent cut
  - basic idea: use whatever communication opportunity presents itself
    - cache-and-forward to deal with episodic connectivity or high mobility
    - data hauling and on-demand instantiated links
      - e.g. autonomous vehicles, smart shells, reindeer networks
  - challenges
    - pure discovery-based operation inadequate: use explicit mission inputs
    - no single routing strategy works well in all situations: adaptation, learning
    - knowledge sharing and synchronization a big challenge
    - cannot assume destination name attributes can be bound at source

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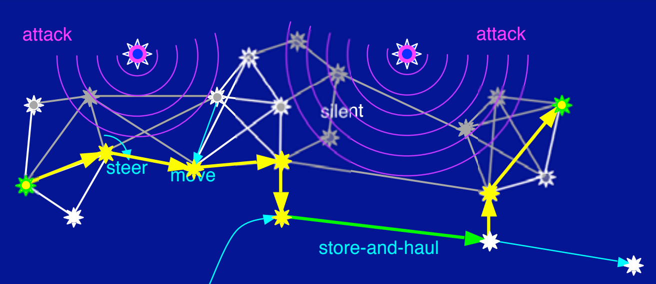
Disruption Tolerant Networking

Expect and Exploit Mobility And Disconnections



- Steer antenna and move nodes around attack
- Autonomous vehicles or smart shells haul data
  - avoid interference and adversarial nodes
  - work around disconnected transit areas

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Slide courtesy: Dr. James Sterbenz

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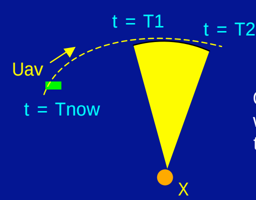
Use of Deductive Database for DTN

Specifying Complex Connectivity, Metadata, And Policy



Ground node X can form a predicted adjacency with some Uav node at t=Tnow provided the trajectory information is known beforehand

- KB allows a succinct expression of a rule to deduce a future adjacency

```
predictedAdjacency :: spindleAdjacency.
S : predictedAdjacency [from->X, to->Uav, adjT->"PREDICTED", upAt->T1, downAt->T2] :-
     walltime (Tnow), Uav [ trajectory -> Trj1], X [ trajectory -> Trj2 ],
     trajectory_crossing(Tnow, Trj1, Trj2, [ T1, T2 ]), !.
```

- Such information can be disseminated and used for routing decisions
- Similarly represent policy about caching, scheduling, discard, and priority

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Slide courtesy: Dr. Prithwish Basu

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Pull from Networking Community

Demand for Automated Reasoning Beyond XG and DTN

- Growing interest for automated reasoning within networks
  - declarative approaches to routing under disruption and uncertainty
  - in-network caching and content-based networking
  - cognitive radio and dynamic spectrum sharing
    - ability to validate conformance to spectrum policy
    - identify opportunities that satisfy applicable policy constraints
  - knowledge-based approach to network management and control
    - tieing-in network decisions to policy, mission, and logistics inputs
  - rule engines for security, e.g., intrusion detection, firewalls
- Need a reasoner/KB focused on networking applications
  - in contrast to existing tools that focus on semantic web, business rules, data mining, and other large server-based optimization
  - robust, reusable, high-performance, preferably open-source
    - usable by networking systems programmers without advanced AI degrees

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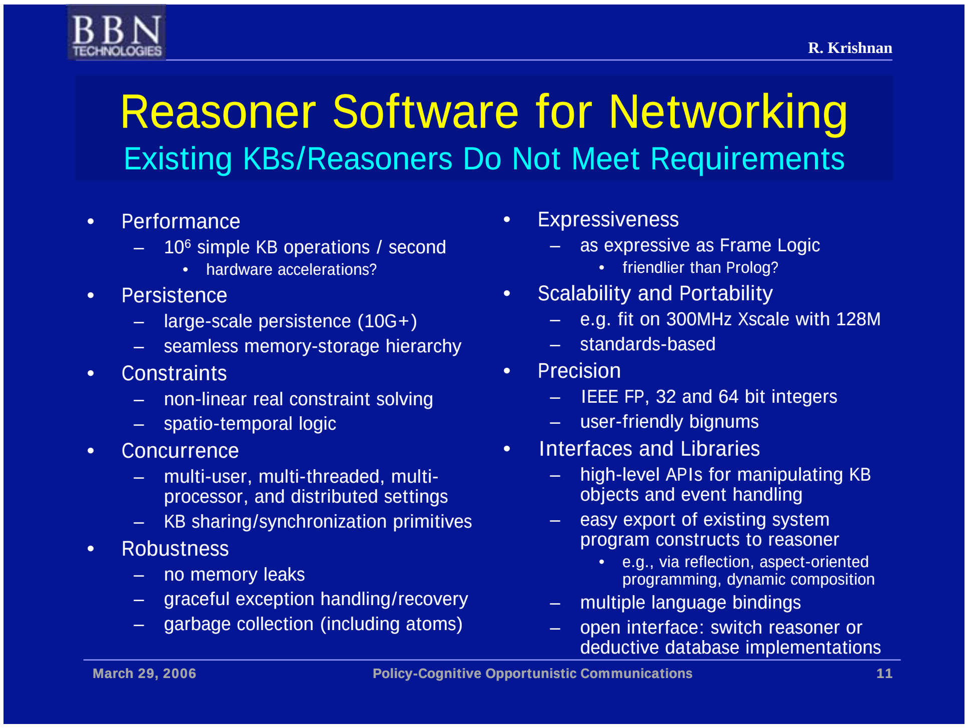
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Reasoner Software for Networking
Existing KBs/Reasoners Do Not Meet Requirements
• Performance
– 10^6 simple KB operations / second
• hardware accelerations?
• Persistence
– large-scale persistence (10G+)
– seamless memory-storage hierarchy
• Constraints
– non-linear real constraint solving
– spatio-temporal logic
• Concurrence
– multi-user, multi-threaded, multi-processor, and distributed settings
– KB sharing/synchronization primitives
• Robustness
– no memory leaks
– graceful exception handling/recovery
– garbage collection (including atoms)
• Expressiveness
– as expressive as Frame Logic
• friendlier than Prolog?
• Scalability and Portability
– e.g. fit on 300MHz Xscale with 128M
– standards-based
• Precision
– IEEE FP, 32 and 64 bit integers
– user-friendly bignums
• Interfaces and Libraries
– high-level APIs for manipulating KB objects and event handling
– easy export of existing system program constructs to reasoner
• e.g., via reflection, aspect-oriented programming, dynamic composition
– multiple language bindings
– open interface: switch reasoner or deductive database implementations
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11