Emerging Wireless Technologies and their Impact on the Future Internet Architecture

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Introduction

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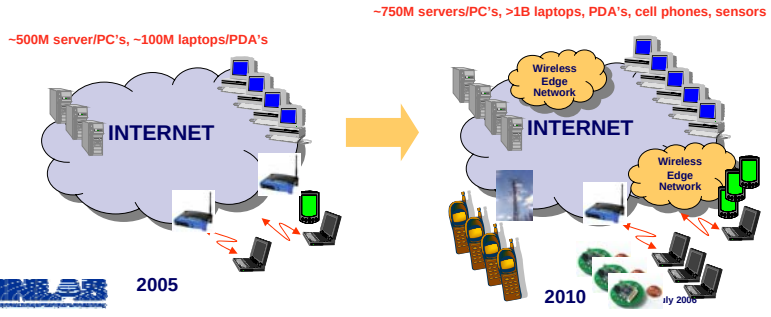
- Opinions expressed are those of the speaker and do not represent an official position of the GENI wireless working group or the NSF…

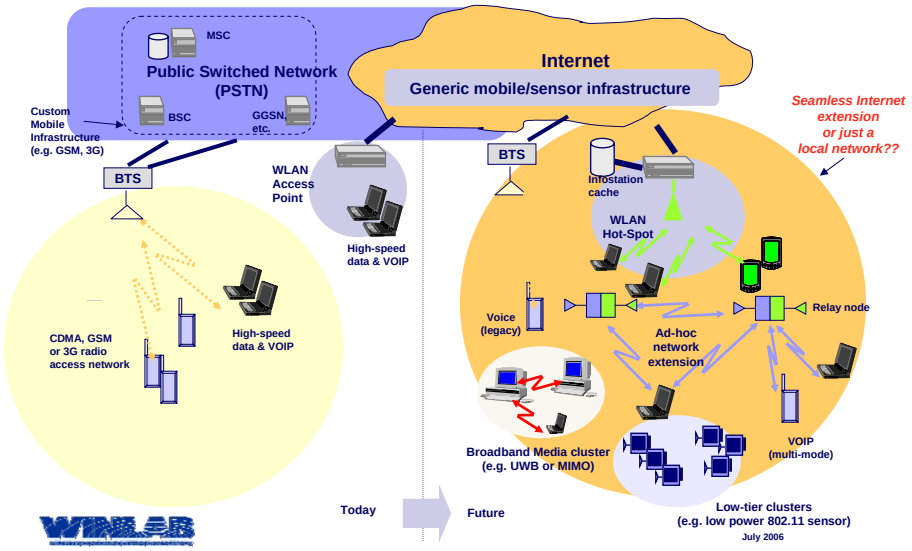
Introduction: Wireless as *the* key driver for the future Internet

- Historic shift from PC's to mobile computing and embedded devices…
  - >2B cell phones vs. 500M Internet-connected PC's in 2005
  - >400M cell phones with Internet capability, rising rapidly
  - New types of data devices (blackberry, PDA, iPoD) – distinctions becoming blurry
  - Sensor deployment just starting, but some estimates ~5-10B units by 2015



Introduction:

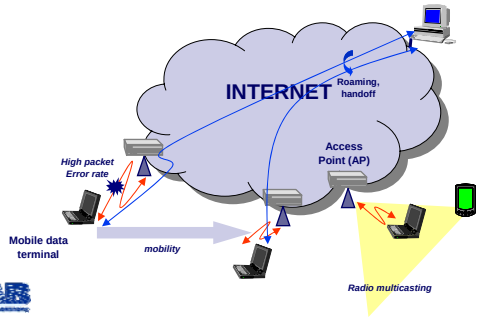
Future Wireless Network Scenario



Emerging Wireless Network Scenarios and Research Drivers

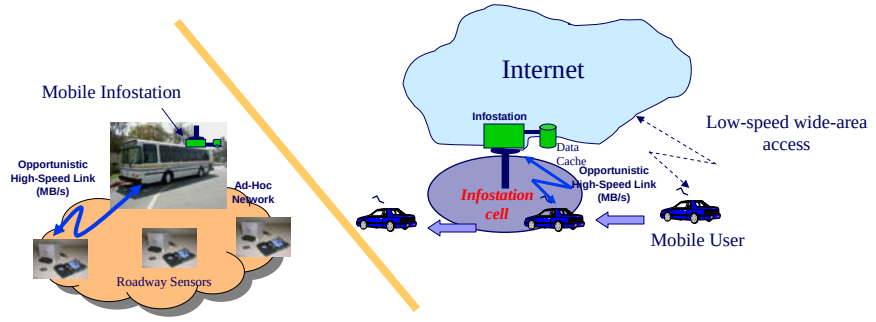
Wireless Scenarios: Mobile Data

- Fast growth of (conventional) mobile data terminals with wireless access link implies a need for new services on the Internet:
  - Terminal mobility (authentication, roaming and dynamic handoff)…mobile IPv6
  - Multicasting …IP multicast
  - Security …e.g. protection against AP spoofing
  - Efficient transport layer protocols (..non TCP)
- Major topic in research & standards during 90's, but actual use is limited



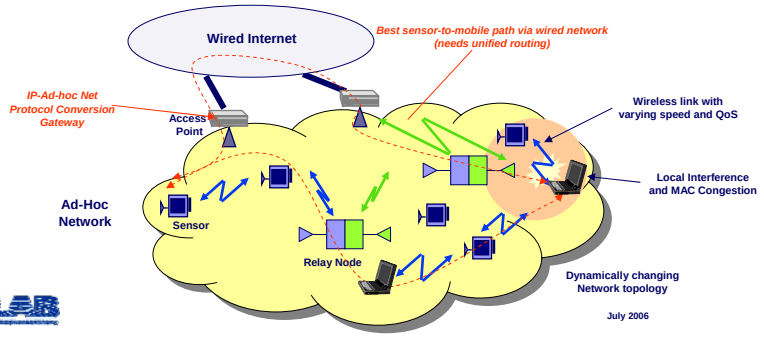
Wireless Scenarios: Mobile P2P

- P2P, 7DS, Infostations, etc. represent another emerging category of mobile applications on the Internet
  - Router mobility
  - Network may be disconnected at times …delayed delivery?
  - Caching and opportunistic data delivery …. In-network storage
  - Content- and location- aware data delivery



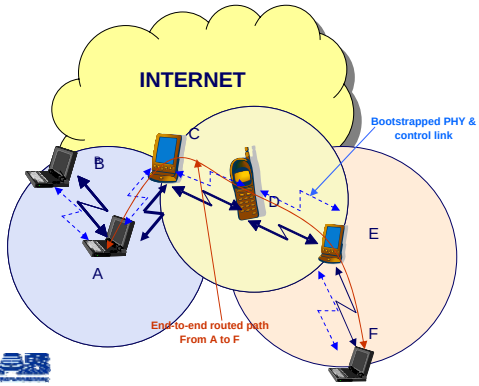
Wireless Scenarios: Ad-Hoc Nets

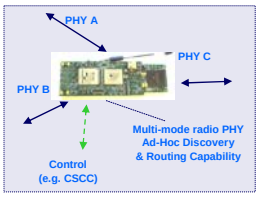
- Ad-hoc nets with multiple radio hops to wired Internet useful for various scenarios including mesh 802.11, sensor, etc.
  - Discovery and self-organization capabilities
  - Seamless addressing and routing across wireless-wired gateway
  - Geographic routing options
  - Support for end-to-end cross-layer protocol approaches where needed
  - Privacy and security considerations



Wireless Scenarios: Cognitive Radio

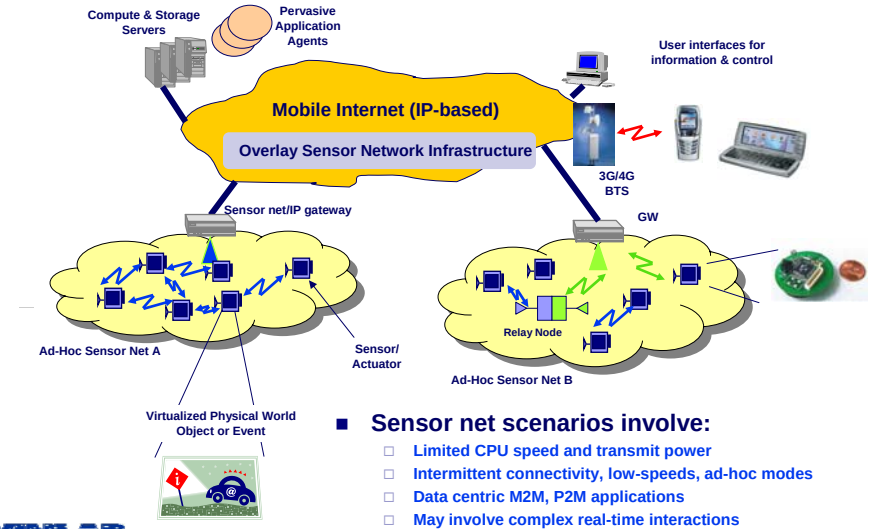
- Cognitive radio drives consideration of adaptive wireless networks involving multi-hop collaboration between radio nodes
  - Needs Internet support similar to ad-hoc network discussed earlier
  - Rapid changes in network topology, PHY bit-rate, etc. → implications for routing
  - Fundamentally cross-layer approach – need to consider wired net boundary
  - High-power cognitive radios may themselves serve as Internet routers…





Adaptive Wireless Network Node
(…functionality can be quite challenging!)

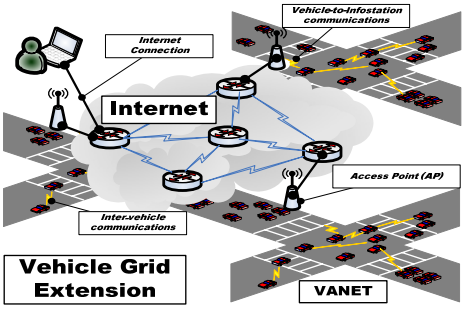
Wireless Scenarios: Sensor Nets and Pervasive Systems



- **Sensor net scenarios involve:**
  - Limited CPU speed and transmit power
  - Intermittent connectivity, low-speeds, ad-hoc modes
  - Data centric M2M, P2M applications
  - May involve complex real-time interactions

Wireless Scenarios: Dense Vehicular Networks

- **Navigation safety: *ad hoc wireless networking***
  - Alerts from neighboring cars
  - Intersection collision avoidance
  - Road sensors to car alerts (icy road etc)
  - Traffic conditions/accidents ahead
  - *Blue corridor* for ambulances
- **Internet access: *WiFI, WiMAX, 3G, Satellite, etc***
- **Car to Car content sharing: *ad hoc + WiFI***
  - Ads, video clips (car torrent; ad torrent)
  - Forensic investigations (kidnappings etc)
  - Sensor platforms (air pollution, chemicals, etc)
- **Distributed Internet games: *ad hoc +WiFI***
- **Prevalent routable address: *geo-address***



Wireless/Mobile/Sensor Scenarios and the Future Internet

- What does this mean for the future Internet?
  - Integrated support for dynamic end-user mobility
  - Wireless/mobile devices as routers (mesh networks, etc.)
  - Network topology changes more rapidly than in today's wired Internet
  - Significant increase in network scale (10B sensors in 2020!)
  - New ad hoc network service concepts: sensors, P2P, P2M, M2M,…
  - Addressing architecture issues – name vs. routable address
  - Integrating cross-layer and cognitive radio protocol stacks
  - Data/content driven networking for sensors and mobile data
  - Pervasive network functionality vs. broadband streaming
  - Power efficiency considerations and computing constraints for sensors
  - Many new security considerations for wireless/mobile
  - Economic incentives, e.g. for forwarding and network formation

Key Technologies & Platforms for GENI Wireless

Experimental Wireless Networks in GENI: Current Research Areas

- Scenarios under investigation by wireless/mobile/sensor network research community include:
  - *Future cellular networks* – alternative radio technologies (WiMax, 4G), open interface for new network and transport protocols, new services (location-aware, media, etc.)
  - *Next-generation wireless LAN* – emerging radio technologies (802.11n, MIMO), improved MAC layer protocols, multicasting, hybrid cellular/WLAN, security
  - *Ad-hoc mesh networks* – use of different radio technologies, spectrum coordination, self-organization, scalable/secure routing protocols, cross-layer, QoS support
  - *Vehicular networks* – real-time inter-vehicle ad-hoc communications, telematics and safety applications, peer-to-peer applications, …
  - *Cognitive radio networks* – interference avoidance methods, networks with multiple radio PHY's, forming adaptive networks, discovery protocols, cross-layer routing, …
  - *Sensor networks* – power efficient protocols, hierarchical topologies, data aggregation and information flows, content-aware routing, service API's, real-world applications
  - *Pervasive systems* – heterogeneous radio technologies, integration of sensors with WLAN/cellular, dynamic binding protocols, closed loop control applications…
- Wireless Networks in GENI should support above scenarios and be flexible enough for multiple simultaneous experiments

GENI Wireless Platforms: Design Considerations

- Design of GENI Wireless platforms and experimental networks based on following considerations:
  - Realistic radio propagation and mobility in representative indoor/outdoor, urban/suburban environments
  - Critical-mass wireless deployments for experiments at scale
  - Support for various types of wireless devices: sensors, mobile users, vehicles…
  - Reflect inherent heterogeneity of wireless technologies (cellular, WiMax, WiFi, etc.)
  - Radio technology agnostic – should support current and future radio standards as well as emerging technologies such as cognitive radio
  - Open API to radio hardware to enable implementation of new networking protocols rather than existing industry standards – leverage existing hardware/ASIC's as components without adhering to today's vertical stacks
  - Programmable platforms designed for downloadable protocols, L2/L3 and above
  - Virtualizable hardware – support for n>>1 slices on same physical infrastructure
  - Upgradable via plug-in radio modules on wireless platforms

Experimental Platforms: State-of-the-Art

- Various experimental platforms available for wireless network research, with programmable radios emerging as a future solution…
  - 802.11/Linux as default wireless client/ad-hoc router for network research during 2000-05
  - Mote/TinyOS most commonly used sensor – commercial Zigbee sensor released recently
  - Other research community platforms such as ORBIT dual-radio node, WARP programmable radio, GNU radio, KU agile radio & near-future cognitive radios, ….
  - Open wide-area radio devices becoming available: WiMax, 3G BSR, …
  - Key issue: *open software interfaces for full control of physical and link/MAC layer*


802.11 embedded node


ORBIT dual-radio node


Radio Forwarding Node

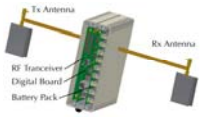

GNU Software Radio


Base Station Router or WiMax BTS


MICA/Mote


Intel Stargate


Rice "WARP" board

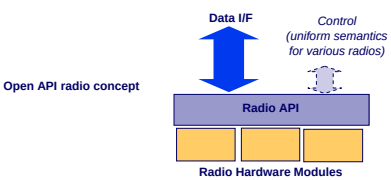


KU Agile Radio


Lucent/WINLAB Cognitive Radio

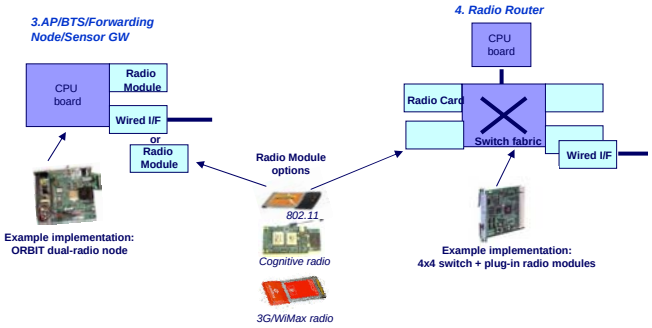
GENI Platforms: Radio Technologies & Open API

- Several radio technologies available for use in networking platforms…
  - Short range: Mote radios, Zigbee, Bluetooth, UWB (802.15.3)
  - Medium range: 802.11a,b,g, MIMO 802.11n, …
  - Long range: GPRS, CDMA2000, 3G/WCDMA, WiMax → future cognitive radio
- Cognitive radios an attractive future option for experimental networks, but technology is still at early stage
- Radio selection determines range/cost/size but generally does not directly affect networking protocol design
- Open API to key MAC/PHY interfaces of critical importance – many current radios bundled with today's protocol standards and need to first be reverse engineered
- GENI approach is to design the network for plug-in compatibility with any current or future radio as long as it follows open API spec



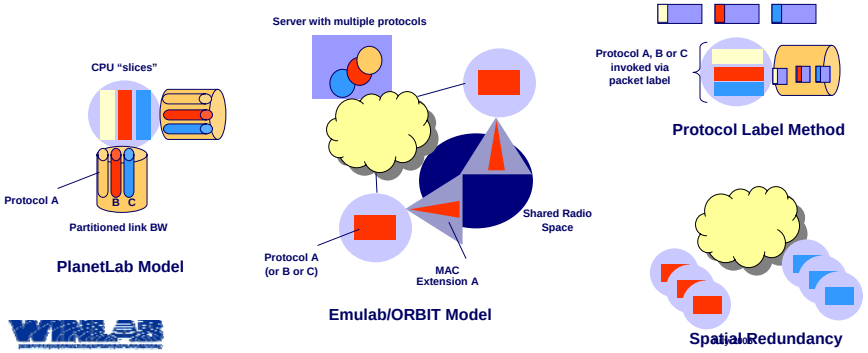
GENI Platforms: Wireless Network Elements

- Wireless network elements needed to support in-network aggregation, switching, forwarding, routing, …
  - Access Points (AP), Base Stations (BTS), Forwarding Nodes & Sensor Gateways, typically with 2 wired or wireless ports
  - More general *n*-port multi-radio router platform with hardware support for routing/switching



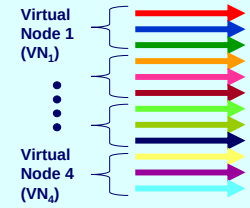
Key Technologies: Network Virtualization

- GENI architecture to support downloadable protocol functionality and multiple experiments
  - Network "virtualization" similar to PlanetLab ("slices") a primary option for core network
  - Other models such as user programmable devices as in Emulab and ORBIT (single user/protocol per node per experiment)
  - Other options such as per packet labels to invoke alternative protocols
  - Wireless devices such as sensors and radio nodes (with MAC) more difficult to virtualize
  - Possible approaches include frequency assignment and spatial redundancy



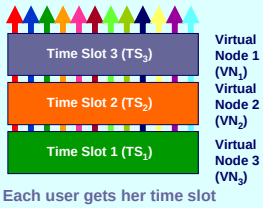
Summary of Wireless Virtualization Techniques

Partition in Frequency Domain (FDMA)



Multiple cards or Single card with channel switching

Partition in Time Domain (TDMA)



Each user gets her time slot (virtual node) on a physical node

Limited by granularity of slots

Partition in Code Domain (CDMA)

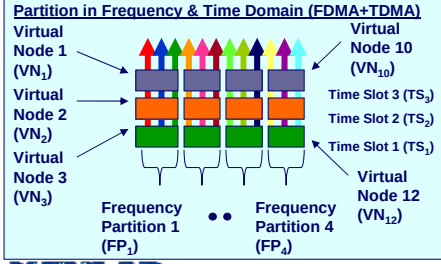
Virtual Node 1 (VN_1)
1011010001.....001
1001011100.....110
1100100001.....011
1110000110.....100

ORTHOGONAL CODES

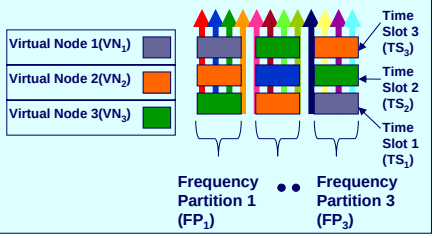
Virtual Node 32 (VN_{32})
1010111000.....101
1111000111.....111
1000001110.....000
1100110010.....110

Each user gets her set of codes Applicable to Cellular networks

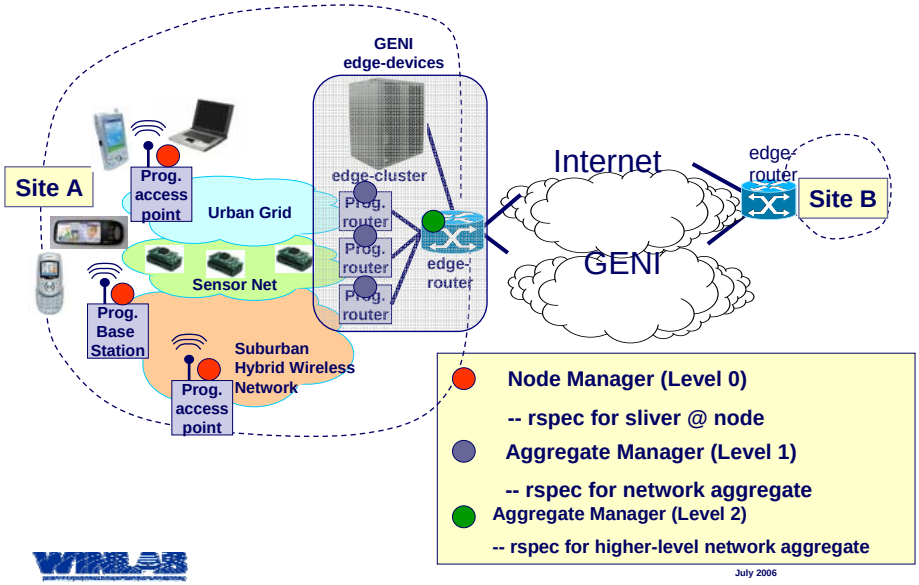
Partition in Frequency & Time Domain (FDMA+TDMA)



Partition using Frequency Hopping (FH)

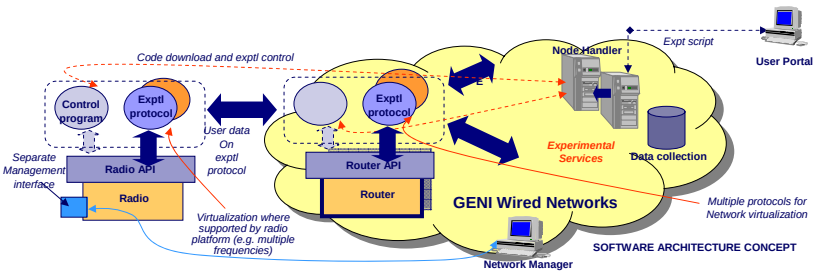


Control & Mgmt Framework for Wireless GENI



Control & Mgmt Software Model in GENI

- Software for GENI wireless platforms
  - Linux open-source on all modules except certain low-power sensors (e.g. Mote)
  - Uniform radio API for control of power, frequency, bit-rate etc. & PHY measurements
  - Uniform soft MAC API for control of packet transmit format/time
  - Experiment downloading software compatible with core network
  - Virtualization software corresponding to platform capability, compatible with core
  - Measurement software for unified PHY/MAC/network statistics for each experiment
  - Separate management interface for remote monitoring and control



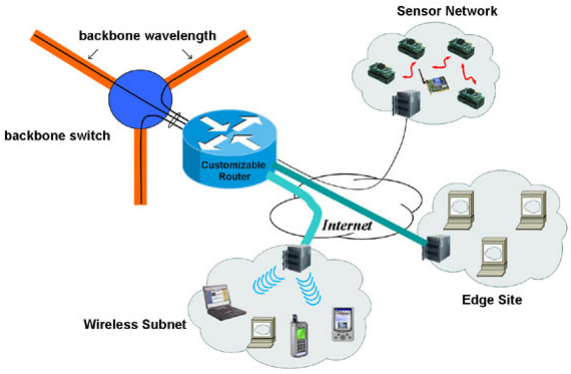
GENI Wireless Subnet Deployment Plans

GENI Implementation: Wireless Subnets – Overall Wireless Deployment Plan

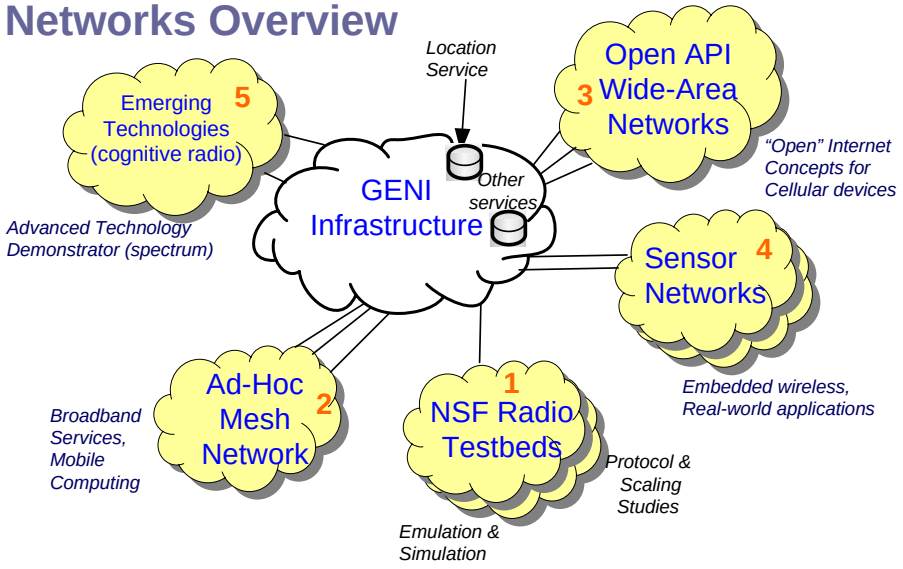
- Five types of experimental wireless networks planned – necessary to support full range of protocol research and to enable new applications
  - 1. **Wireless emulation and simulation** (repeatable protocol validations)
  - 2. **Urban 802.11-based mesh/ad-hoc network** (real-world networking experience with emerging short-range radios)
  - 3. **Wide-area suburban network** with both 3G/WiMax (wide area) and 802.11 radios
  - 4. **Sensor networks** (…application specific, specific system TBD via proposal process; may include environmental, vehicular, smart spaces, etc.)
  - 5. **Cognitive radio network** – advanced technology demonstrator (…adaptive, spectrum efficient networks using emerging CR platforms)
  - …also some **common network facilities** such as location & dynamic binding services
- Each network at a different geographic location – new spectrum allocation may be needed at some sites

GENI Implementation: System Outline

- GENI intended to serve as programmable experimental infrastructure
  - Nationwide coverage with at least 25 PoP's
  - Several peering points with current Internet
  - Edge routers and backbone switches with fiber
  - Fully programmable, virtualizable routers as the main building block
  - ~5-6 wireless sub-networks covering urban and suburban areas

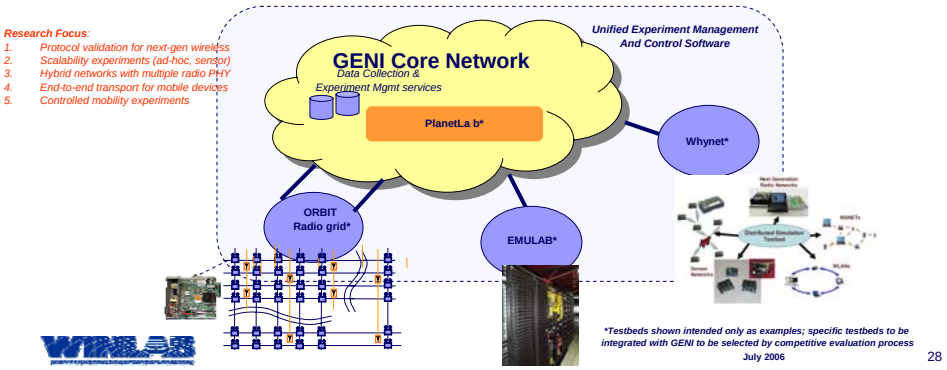


GENI Implementation: Wireless Sub-Networks Overview

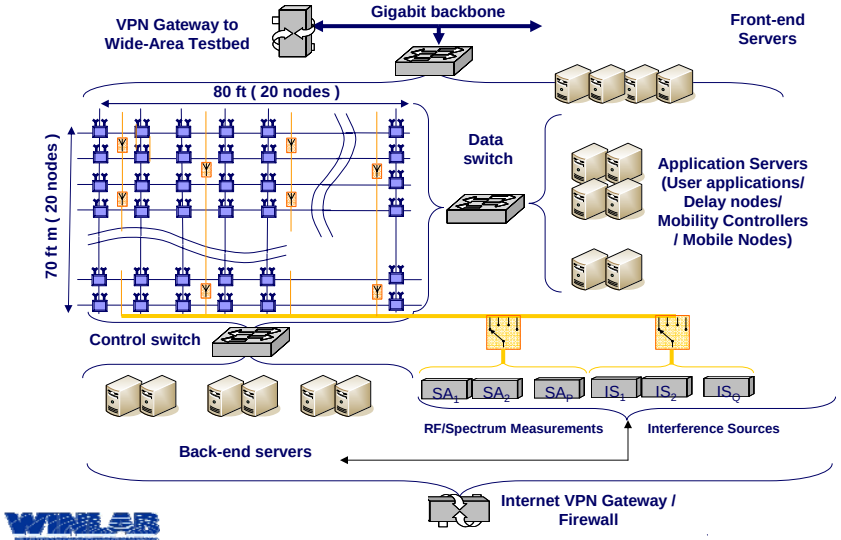


GENI Implementation: Wireless Emulators

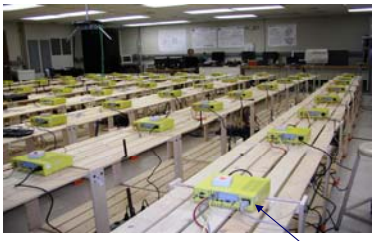
- Large-scale emulators and simulators provide important protocol testing capabilities when connected to GENI
  - Enables end-to-end protocol tests with large numbers of nodes
  - Reproducible experiments with extensive data collection; virtualization per experiment



Wireless Network Emulators: ORBIT Radio Grid as an Example

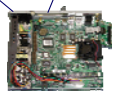


Wireless Network Emulators: ORBIT Radio Grid (cont.)



64-node radio grid prototype at Busch Campus (8/04)

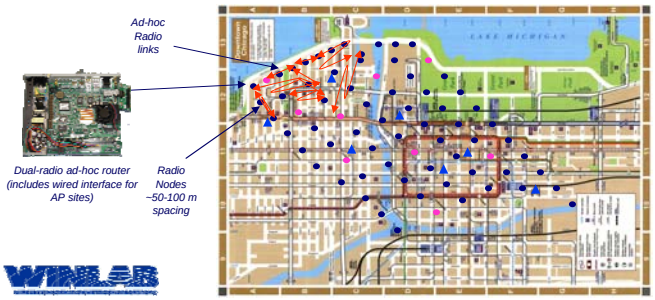
400-node radio grid system at Tech Center II (construction completed 7/05)



ORBIT radio node hardware

GENI Implementation: Open API Urban Ad-Hoc Mesh

- Ad-hoc wireless network providing full coverage of high-density urban area ~ 10 Km**2
  - Enables experimentation with mesh network protocols & broadband mobile applications
  - Dual-radio forwarding node as building block
  - Open API 802.11 with soft MAC, virtualization by frequency or space
  - Services for running expts, data collection, frequency assignment and spectrum meas

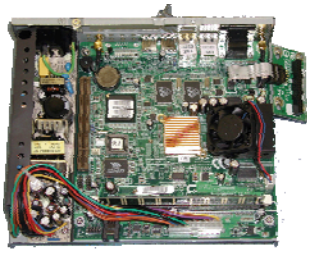


Research Focus:

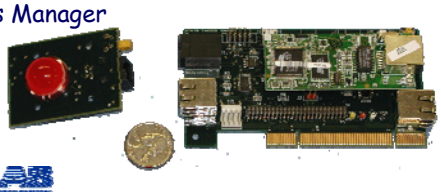
1. *Ad-hoc routing*
2. *Self-organization & discovery*
3. *Cross-layer optimizations*
4. *MAC layer enhancements*
5. *Security with ad-hoc routing*
6. *Broadband QoS*
7. *Impact of mobility*
8. *Real-world application studies*

Open API Radio Node: Example Implementation

ORBIT Radio Node
with integrated Chassis Manager



Chassis Manager



Non-Grid Node
Chassis Manager
(w/ GPRS control)

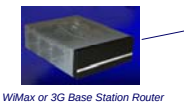
GENI Implementation: Vehicular Mobility

Example Vehicular Deployment (ORBIT outdoor)

- System leverages urban mesh infrastructure for Internet connectivity
- Campus/city-wide deployment (~100s mobile nodes)
  - private cars, taxi fleet, campus shuttles, buses
- On board equipment:
  - Radios: conventional (WiFi, 802.11p, Bluetooth, 3/4G, Satellite); next generation (MIMO, cognitive radios, etc);
  - Sensors: GPS; video cameras; acoustic sensors; on board sensors; environment monitoring, etc.
  - Sensed data filters (for automatic event detection): e.g., LPR (license plate recognition), driver's voice recognition
  - Data server, harvester: classify and store events; P2P applications (eg, epidemic dissemination; forensic data search, etc)

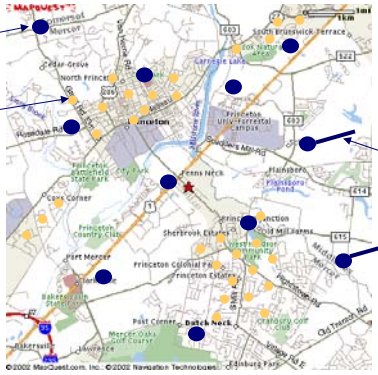
GENI Implementation: Open API Wide Area Mobile Network

- Open API wide-area wireless network to explore alternatives to cellular, hybrids with WLAN, Infostations, new mobile applications…
  - Suburban coverage ~50 Km**2 using ~10 wide-area BTS's + ~100 short-range AP's
  - Open API 3G or WiMax BTS and dual-radio 802.11 node as building blocks



WiMax or 3G Base Station Router

802.11 Relay Node Platform



Open API 3G/WiMax BTS

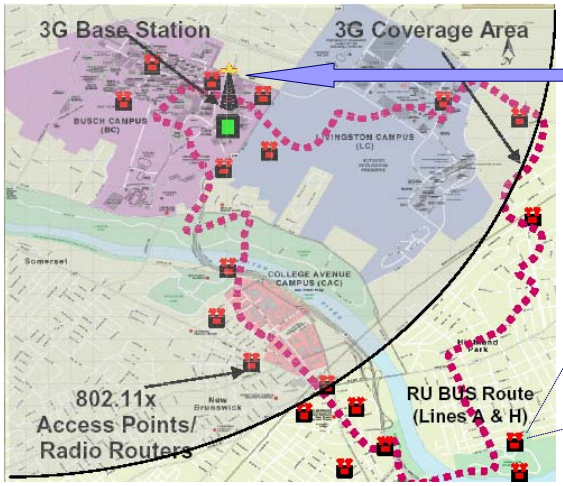
802.11 relay node or AP

Connections to GENI Infrastructure

Research Focus:

1. *Internet transport for 3G/cellular*
2. *Mobility support in future Internet*
3. *Hybrid 3G/WLAN handover, etc.*
4. *Multicasting*
5. *Transport layer for wireless*
6. *Security in future 3G/4G*
7. *Information caching and multimedia*

Open API Cellular: Example Implementation



Open API, IP based BSR
(Lucent Technologies)

Short-range Open API
Node (WINLAB)

GENI Implementation: Sensor Network Types and Features

- Deployed regional testbeds (2-3), each w/ ~100s of wireless nodes (wideband-32bit platforms) that both host sensors and act as backbone to subnet kits
  - Linux-based embedded PCs with meterological sensors
  - 802.11a/b/g interface with multi hop wireless networking backbone
  - second, low-power sensor net radio (802.15.4 or equivalent) to talk to in-situ nodes

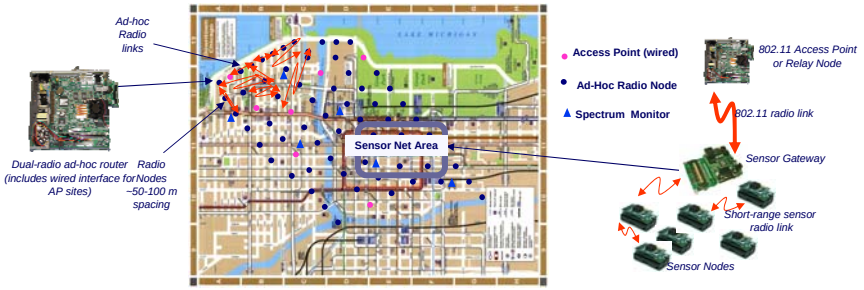
  => goal is to allow sensors to be deployed in-situ and used in real-world applications
- Sensor subnet kits (50), each with ~100 application specific nodes
  - design for hardware platform, standard pluggable sensor packs, expansion boards
  - kits will be distributed and purchasable by researchers on research funds

  => goal is to allow diverse set of applications that feed traffic and service requirements into GENI
- Indoor reconfigurable labs (2), each with ~100s of wireless nodes (both narrowband-8bit and wideband-32bit platforms) with very basic sensors
  - Tmote Sky sensors running TinyOS with light, temp, humidity sensors
  - Web-based interface for programming, logging, debugging

  => goal is to allow controlled, reproducible experiments using data, models, and applications from regional testbeds and kits

GENI Implementation: Urban Mesh + Sensor Network

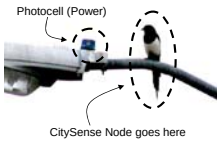
- 2-3 sensor network projects to be selected via proposal process for integration into urban mesh deployment
  - Sensor network experiments will leverage 802.11 mesh or 3G wide area infrastructure in items 2,3
  - Provide "user deployment kit" with platforms including sensor nodes and sensor/WLAN or sensor/3G gateway



Sensor Net Testbeds: Deployment Examples

- Support urban-scale measurement and diverse applications
- Linux-based embedded PCs with 802.11a/b/g and 802.15.4
  - Mounted on top of light poles, buildings, etc.
  - Possible sensor types include meteorological, environmental, pollution, etc.
- Web-based interface for job scheduling, debugging, profiling
  - Open resource for the sensor network community

Harvard/BBN CitySense deployment plan



Metrix embedded PC

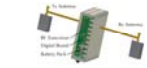
Vaisala meterological sensor

Sensor Net Testbeds: Experimental Kits

- Support diverse set of applications
  - Capture applications not amenable to regional testbed
  - Enable many researchers to hook-in to GENI, sharing common design
- Several designs
  - Inexpensive, small 8-bit platform (e.g., running TinyOS)
  - More capable 32-bit platform (e.g., running linux)
  - Sensors include standard packs (for identified applications) and expansion boards
  - Will connect to regional testbed and to GENI edge nodes
- Two distribution models
  - Some distributed as part of GENI, will have strong requirements on providing data and integrating with testbeds
  - Designs made publicly available; suitable for researcher purchase
- Standard software to interface to GENI
  - Allow nodes to be reused by external researchers when not used by application user
  - Sensornet data can flow over GENI backbone

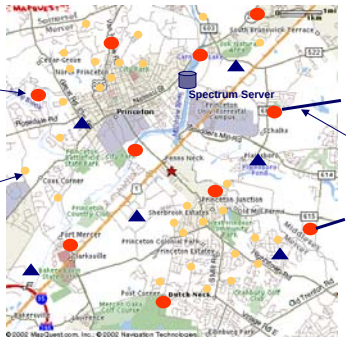
GENI Implementation: Cognitive Radio Technology Demonstrator

- Advanced technology demonstrator of cognitive radio networks for reliable wide-area services (over a ~50 Km**2 area) with spectrum sharing, adaptive networking, etc.
  - Basic building block is a cognitive radio platform, to be selected from competing research projects now in progress and/or future proposals
  - Requires enhanced software interfaces for control of radio PHY, discovery and bootstrapping, adaptive network protocols, etc. – suitable for protocol virtualization
  - New experimental band for cognitive radio (below 1 Ghz preferable)



Cognitive Radio Network Node

Cognitive Radio Client



Cognitive Radio Network Node

Cognitive Radio Client

Spectrum Monitors

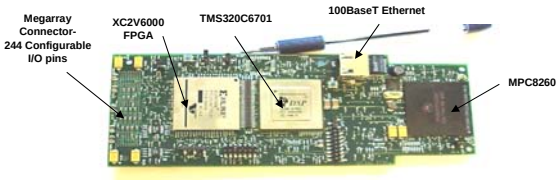
Connections to GENI Infrastructure

Research Focus:

1. *New technology validation of cognitive radio*
2. *Protocols for adaptive PHY radio networks*
3. *Efficient spectrum sharing methods*
4. *Interference avoidance and spectrum etiquette*
5. *Dynamic spectrum measurement*
6. *Hardware platform performance studies*

Cognitive Radio Technology:
Hardware Platforms

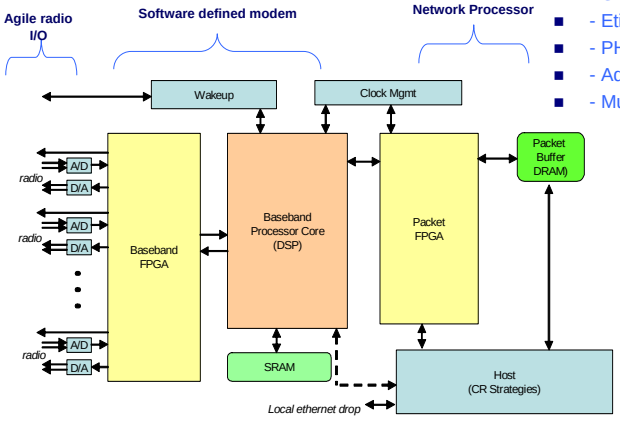
- Next-generation software-defined radio supporting fast spectrum scanning, adaptive control of modulation waveforms and collaborative network processing
- Facilitates efficient unlicensed band coordination and multi-standard compatibility between radio devices



Bell Laboratories Software Defined Radio (Baseband Processor)
Courtesy of Dr. T. Sizer

Cognitive Radio Technology:
WINLAB prototype

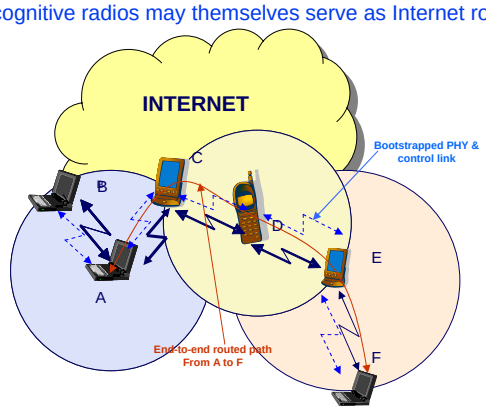
Requirements include:
- ~Ghz spectrum scanning,
- - Etiquette policy processing
- - PHY layer adaptation (per pkt)
- - Ad-hoc network discovery
- - Multi-hop routing ~100 Mbps+



WINLAB's "network centric" concept for cognitive radio prototype
(..under development in collaboration with GA Tech & Lucent Bell Labs)

Cognitive Radio Technology: Adaptive Wireless Network Protocols

- Cognitive radios will have the capability of forming collaborative ad hoc networks with considerable flexibility in PHY, MAC
  - Incentives for spectrum conservation and collaboration (vs. competition)
  - Rapid changes in network topology, PHY bit-rate, etc. → implications for routing
  - Fundamentally cross-layer approach – need to consider wired net boundary
  - High-power cognitive radios may themselves serve as Internet routers…



GENI Project: Future Roadmap

- NSF MREFC preparedness projects currently under way
  - Several working groups, each producing system specs and deployment plans
  - Initial design work to be completed by 2Q07
  - Subject to next-stage MREFC funding, start construction in late 07/early 08
- NSF "FIND" program for research on new Internet protocols
  - Projects starting 3Q06
  - Fundamental research on end-to-end architecture & protocols
  - Experimental component, expected to drive GENI usage
- Proof-of-concept prototyping activities and existing network testbeds
  - PlanetLab, Emulab, ORBIT, MoteLab, ….
  - Integrating wireless and wireless testbeds, e.g. PlanetLab + ORBIT
  - Virtualization techniques for wireless networks
  - Cognitive radio hardware platforms and software stacks
  - …other
- Collaborations with European research groups welcomed ….
  - Joint work on key experimental network technologies
  - Federated testbeds…

Web Sites for More Information:

- WINLAB: www.winlab.rutgers.edu
- ORBIT: www.orbit-lab.org
- GENI: www.geni.net