System Engineering Document for Wireless Subnets

GDD-06-21

GENI: Global Environment for Network Innovations

September 15, 2006

Status: Draft (Version 1.0)

Note to the reader: this document is a work in progress and continues to evolve rapidly. Certain aspects of the GENI architecture are not yet addressed at all, and, for those aspects that are addressed here, a number of unresolved issues are identified in the text. Further, due to the active development and editing process, some portions of the document may be logically inconsistent with others.

This document was prepared by the Wireless Working Group.

Editor:

Chip Elliott, *BBN Technologies*

We also acknowledge the very helpful comments and suggestions from Ivan Seskar, Winlab.

Table of Contents

1 Purpose of this Document

This document is the System Engineering Document for the GENI Wireless Subnets. It is currently in early draft form, for discussion purposes only.

This document is derived from the higher-level System Architecture for the GENI Wireless Subnets, and provides the following descriptions for each of the GENI Wireless Subnets:

- Functional decomposition into subsystems and components
- Requirements for each subsystem and component, which are ultimately derived from the experimental needs of the research community for the GENI wireless subnets
- External interfaces for each subsystem and component
- Hardware definition for each subsystem and component
- Software definition for each subsystem and component

This document is intended to be used for the following purposes:

- Provide concrete details to spur discussion within the GENI Wireless Working Group
- Help identify those parts of the GENI Architecture that require further definition
- Provide Basis of Estimate (BOE) inputs to the GENI Statement of Work (SOW)

2 Referenced Documents

This section identifies the location of this System Engineering Document within the GENI document tree, and lists all documents referenced herein. It includes both GENI documents that form part of the specification for this document, as well as other miscellaneous documents that are included for information or reference only.

2.1 This Document within the GENI Document Tree

Figure 2-1 below shows how this document fits into the overall document tree for the GENI project.

To be supplied.

Figure 2-1. This document within the GENI Document Tree.

2.2 GENI Documents

The following documents are referenced within this document, and form part of the specification provided by this document. This document has been derived from the exact versions of the documents cited below (e.g. by date of issue or draft number). If these references are out of date, this document may be incompatible with the newer references.

[G-des] GENI: Design Principles, GDD-06-08 (Draft June 2006)

[G-arch] GENI Architecture

[G-gmc] GENI Management Core, Version 0.05 (July 8, 2006)

[G-gmcr] GENI Management Core Requirements (July 18, 2006)

[G-sec] GENI Security Architecture (not identified)

[G-gims] GENI Instrumentation and Measurement System (GIMS) Specification, Version 0.3 (July 5, 2006)

[G-warch] GENI Wireless Subnet Architecture

[G-back] GENI Backbone Working Group: Software Architecture (July 10, 2006)

2.3 Other References

Other documents cited in this document, which do not form part of this specification for this document, are listed below. Changes to these referenced documents will not affect the specifications provided in this System Engineering Document.

[xxx] xxxxx.

3 Overview of the GENI Wireless Subnets

This section provides an overview of the various GENI Wireless Subnets, and their experimental goals and approaches. The following subnets are included:

- GENI Urban Mesh Subnets
- GENI Suburban Wide Area Subnet
- GENI Application-Specific Sensor Subnets
- GENI Cognitive Radio Subnets
- GENI Wireless Emulation Subnets

It then provides a mapping between these subnets and the constituent subsystems (both hardware and software), identifying elements that (a) are common across multiple subnets, (b) have a common baseline but require adaptation for a given subnet, or (c) must be uniquely developed for a specific subnet.

3.1 Catalog of GENI Wireless Subnets

The following sections briefly describe each type of GENI Wireless Subnet in turn, providing a high-level overview of each subnet and a basic description of its goals. Later sections within this System Engineering document provide the detailed description of each sub-system within these various subnets.

Certain basic themes run throughout these subnets, as follows:

- **Kits** – Each subnet is made of wireless nodes which are built as 'kits'. These kits can then be used in laboratory experiments, field installations, or controlled experimentation facilitys. It is intended that a given type of kit be common across all its uses.
- **Field Installations** – Several forms of subnet will be deployed in the "field," i.e., in urban or suburban areas. These installations are relatively large and will be long-lasting. They provide live GENI experimental facilities "in the wild". It is expected that a subcontract would be issued to construct and operate a given field installation.
- **Controlled Experimentation Facilities** – Several forms of subnet will be deployed in specialized facilities that allow controlled, repeatable experiments within the GENI wireless context. Since RF experimentation "in the wild" generally does not support the repeatability required for such experiments, these facilities will be housed in specialized rooms (RF shielded) to prevent external interference, with controllable sources of RF interference for those experiments involving noise.

3.1.1 GENI Urban Mesh Subnet

The GENI Urban Mesh Subnet allows experimentation with "urban mesh" network architectures, as well as multi-hop radio networks, access to the GENI infrastructure from moving vehicles, and mobile ad hoc networks (MANETs). This subnet will be provided in both Kit and Field Installation form (but not in Controlled Experimentation Facilities???).

Figure 3-1 provides a high-level system diagram of an Urban Mesh subnet in a Field Installation. Each wireless node in this installation is based on the appropriate kit, housed in suitable packaging for urban deployment. It is expected that the largest Field Installation in GENI will contain approximately 1,000 wireless nodes.

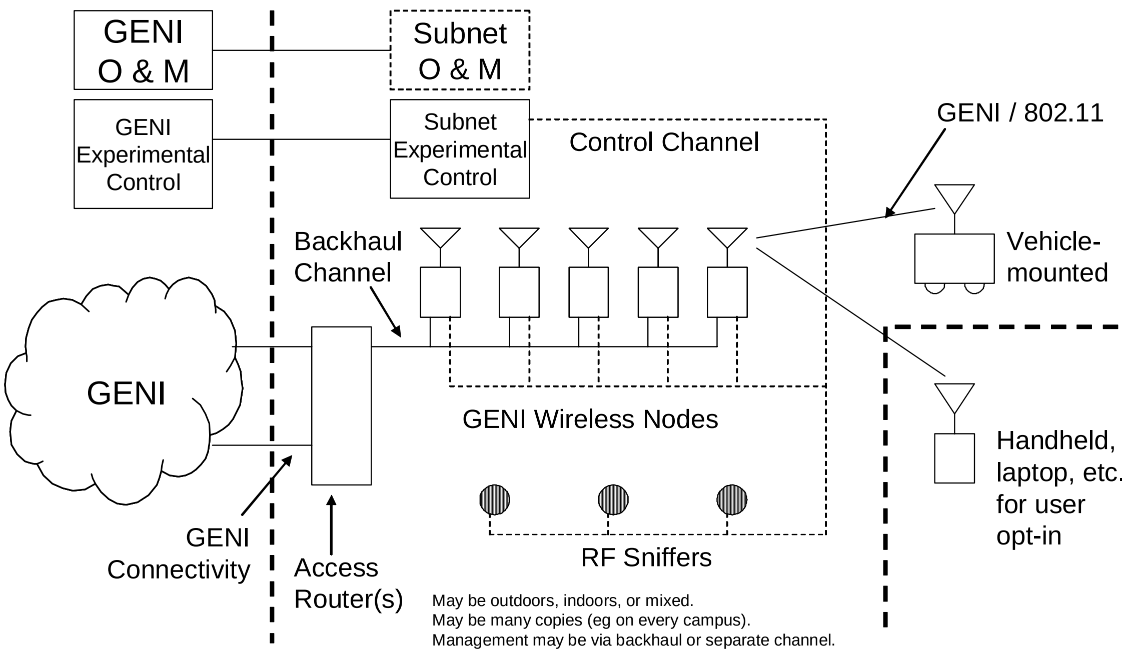

Figure 3-1. GENI Urban Mesh Subnet (Field Installation).

As shown, the Field Installation also contains a number of subsystems in addition to the wireless nodes themselves. Everything within the dashed lines is considered part of the Field Installation, including one or more GENI Access Routers, RF sniffers, subnet experimental control (GMC), operations and management (O&M), and wireless nodes mounted in vehicles such as buses or taxis.

The Field Installation includes highspeed "backhaul channels" that allow nodes to send GENI traffic directly (not multi-hop RF) to the Access Routers. These backhaul channels can be used for mesh experimentation; they can be ignored by slices that are experimenting with multi-hop RF technologies.

The Field Installation also includes highspeed "control channels" that allow new software images to be downloaded into wireless nodes (as slivers), and that allow measurement data to be extracted. The installation is also populated with a number of RF sniffers which measure ambient RF spectra and which provide these measurements as part to the experimental control subsystem as a reliable profile of RF activity during experimental activities (whether generated by the experiment itself or externally induced).

3.1.2 GENI Suburban Wide Area Subnet

To be supplied.

3.1.3 GENI Cognitive Radio Subnet

The GENI Cognitive Radio Subnet allows experimentation with networks formed from cognitive radios. This subnet will be provided in three forms: Kit, Controlled Experimentation Facility, and Field Installation form.

Figure 3-2 shows the Cognitive Radio Subnet in its Controlled Experimentation Facility. It is expected that a relatively modest number of GENI Cognitive Radio (CR) Kits will be produced; some will be used to populate the facility. We expect the number of CR Kits in the facility to be on the order of 10 nodes. The facility itself will be an RF-shielded anechoic chamber. It will also contain RF sniffers (receivers) and stimulators (transmitters) to monitor and influence the RF environment within the chamber. The nodes will be attached to the larger GENI network infrastructure by an Access Router (small version), and managed by an Experimental Control subsystem.

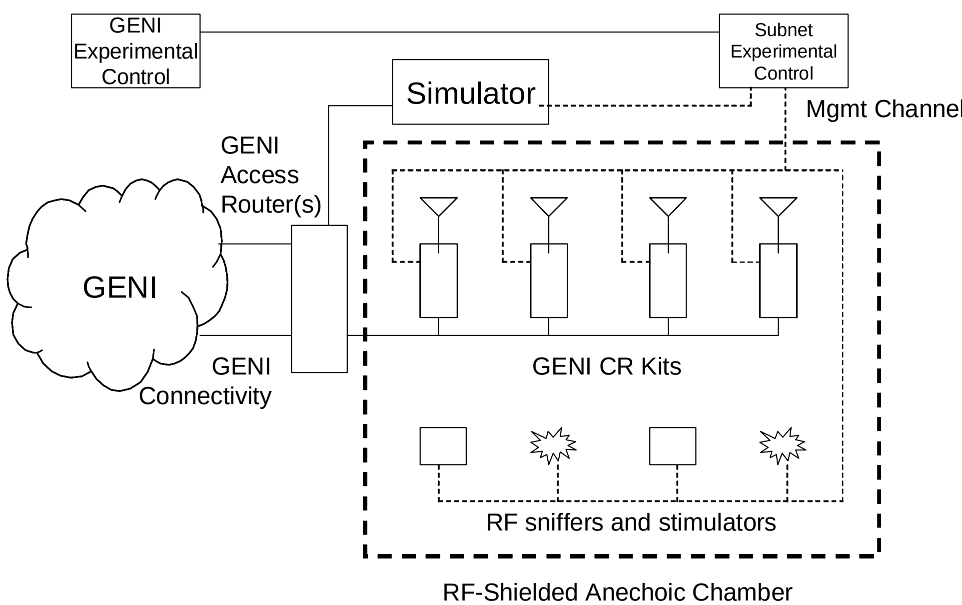

Figure 3-2. Cognitive Radio Subnet in Controlled Experimentation Facility.

Note that the Controlled Experimentation Facility also contains a Cognitive Radio simulator, which can be used by experimenters to perform high-resolution modeling of the behavior of CR Kits under various conditions. It is expected that this simulator be a computational platform (e.g. cluster) into which experimental software slivers may be loaded. The facility will provide realistic radio models (antennas, propagation, multipath, interference, etc.) so that the software may be shaken down before real experiments in the anechoic chamber. The number of nodes to be simultaneously modeled in this simulator are currently TBD, as are the details of the types of modeling to be supported.

Figure 3-3 depicts a Cognitive Radio Subnet in a field installation. It looks somewhat like an Urban Mesh installation but is populated with CR Kits instead of the Urban Mesh variant of GENI Wireless Nodes. We believe it is desirable for these CR Kits to be simple “plug-in” upgrades to GENI Wireless Kits so that existing field installations of GENI Urban Mesh subnets can be used for cognitive radio trials (without the expense of obtaining permission from additional communities, adding new devices to pole tops, etc.).

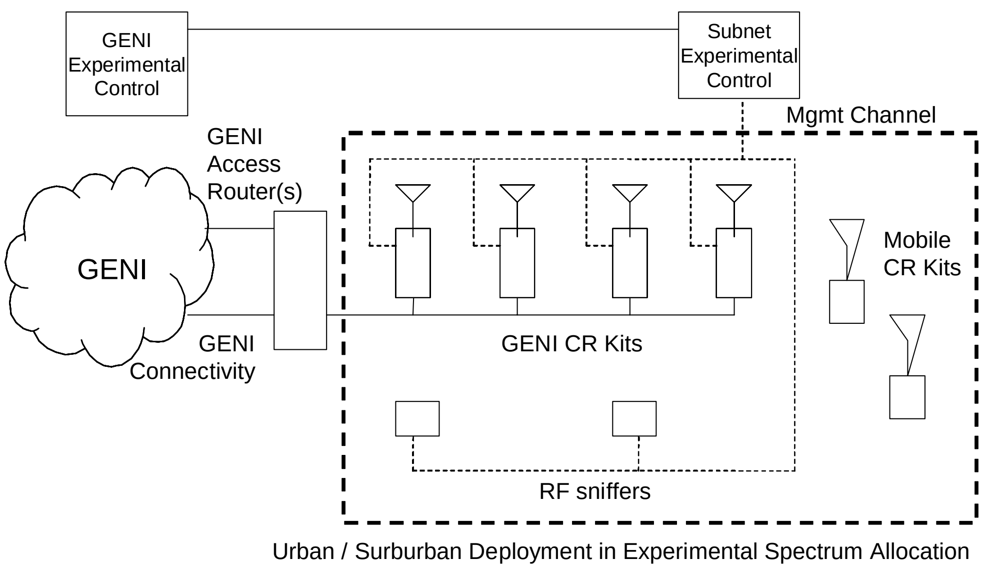

Figure 3-3. Cognitive Radio Subnet in Field Installation.

Spectrum policy is likely to be a real issue for field installations of cognitive radios, since much of the operation of such radios is under the control of experimental software. It would be desirable to obtain an experimental spectrum allocation from the FCC for cognitive radio field installations; additionally, the hardware should probably be designed so that compliance with important FCC policies can be readily ascertained no matter what what software runs on the platform.

3.1.4 GENI Application-Specific Sensor Subnets

To be supplied.

3.1.5 GENI Wireless Emulation Subnets

To be supplied.

3.2 Equipment Matrix for GENI Wireless Subnets

This section provides a matrix that tabulates the specific types of equipment, and facilities, across the various GENI wireless subnets. This table specifies equipment that will be constructed as part of the GENI construction effort – however, it does not proscribe any additional uses of the GENI wireless subnet equipment!

IMPORTANT – This table is important but is not yet understood or agreed!

		Urban Mesh			Suburban Wide Area	Sensor		Cognitive Radio		Emulation
		Field	Local	Kit		Field	Kit	Facility	Kit	
Subnet O&M		✓			✓	✓		✓		✓
Subnet Experimental Control		✓	✓		✓	✓		✓		✓
GENI Access Router	Big	✓								
	Small		✓		✓	✓		✓		✓
Baseline GENI Wireless Node		✓	✓	✓		✓	✓	✓	✓	✓
Radio Cards	802.11	✓	✓	✓						✓
	Sensor					✓	✓			✓
	Cognitive							✓	✓	✓
RF Test Equipment	RF Sniffer	✓				✓		✓		✓
	RF Emitter							✓		✓
Vehicle Mounted Nodes		✓								
Controlled Experimentation Facilities								✓		✓

4 System Engineering Approach for the GENI Wireless Subnets

This section describes the design philosophy that has guided system engineering for the GENI Wireless subnets. This philosophy has a number of concrete implications, e.g., on the software design and hardware selection for wireless nodes. These concrete implications are discussed in the relevant subsections below.

Important Note: This system engineering approach has been documented for discussion only. It has not yet been agreed to by the GENI Wireless Working Group.

4.1 Embrace GENI Design Philosophy

The GENI *Design Principles* [G-des] call for a specific set of principles to be applied in the design and construction of GENI. These principles supply the high-level guidance that shapes this system engineering approach. We quote from that document:

- **Start with a well-crafted system architecture.** The more complex the factorization of the system into a set of component building blocks, the greater the risk that the interdependencies among components will become unmanageable. The success of the Internet itself can be traced in large part to the fact that its architecture allowed components to evolve independently of each other. The GENI architecture is guided by the same design principle, whereby independent technologies can be plugged into the management framework with virtually no dependency on each other, and independent distributed services to be developed without heavy-weight coordination.

- **Build only what you know how to build.** Because software is plastic, there is a tendency towards feature creep; it is easier to specify the features a system "must" have, than it is to make those features work together. Left unchecked, this can result in systems that are simply too complex to work. There will be those who will complain that we are doing too little, beyond what we already understand. Our answer is, exactly, but the synthesis of these elements is revolutionary.

- **Build incrementally, taking experience and user feedback into account.** It is a well known result of computer science research that in software or hardware construction efforts, errors are cheapest to fix when they are caught early. The best way to do that is to put the system into active use at the earliest possible moment, gain live experience with the system, and incrementally evolve the system based on what you learn.

- **Design open protocols and software, not stovepipes.** A huge point of leverage for us, versus other examples of large scale software systems construction, is that the users of the facility—the computer science research community—are themselves capable of fixing and enhancing the system, if we give them the right tools. This is unique to the case where we build systems for ourselves, versus building systems for other people; project meltdown is much more likely if the result is take it or leave it. We aim to build a system that continues to evolve in meaningful ways after GENI construction is complete. All of the successful examples of large-scale systems being successfully delivered by the computer science research community have the property that they continued to be modified by their user community, well after initial delivery.

- **Leverage existing software.** While some aspects of GENI will need to be implemented from scratch, we expect to be able to leverage significant amounts of existing software. It is essential that we take advantage of such software, and to the extent possible, do so in a way that allows us to also leverage the support systems already in place to keep this software up-to-date. Even adapting, rather than directly using an off-the-shelf software package takes time, and raises the question of who now supports the modified package. Similar arguments favor commercially available hardware.

4.2 Reduce Cost and Risk for Construction / Installation

There are a variety of types of GENI wireless subnets, and most or all will be specially built and deployed for the GENI infrastructure. This has obvious cost and risk implications.

If each subnet is designed and built from scratch, the overall result will cost more than if they have shared components. On the other hand, when components are shared, a failure or delay in design of a shared component will cause problems for all subnets relying on that component.

4.3 Maximally Leverage Other GENI Components

The GENI wireless subnets contain a large number of components, many of which are similar to (or potentially identical with) components from other parts of the GENI system. For example, wireless “urban mesh” nodes contain a sliverable, reprogrammable processor that is at a high level quite similar to that in a GENI endpoint computer (e.g. a PC). As another example, a large-scale GENI wireless subnet will need a GENI access router that ties all the subnet nodes into the larger GENI network transport (backbone).

Our approach is to maximally leverage other GENI components, i.e., to attempt to use other GENI components with little or no change. This has the following concrete implications:

- The GENI wireless nodes will be, in so far as is possible, unmodified GENI endpoint computers augmented with radio interfaces in order to act as wireless subnet nodes. Note that this implies that the wireless nodes will be relatively high-end, general purpose computers (e.g. running Xen etc.) instead of small, embedded devices.

- The GENI access routers will be, so far as is possible, unmodified GENI routers. Small wireless subnets will use small GENI routers; the big GENI wireless subnets will use GENI backbone routers. These routers will need to be augmented with “access router” functionality if that is not already provided, i.e., the ability to multiplex / demultiplex large numbers of GENI devices (wireless nodes) into a transport channel.

- The GENI Experimental Control will be, so far as is possible, identical to control platforms for the other GENI subnets. If possible, it will employ the same hardware and software suites as the other subnets employ, as will the data repositories associated with the experimental control.

4.4 Share GENI Wireless Components

There are a variety of GENI wireless subnets, with contain a variety of wireless node types and control & management systems. As discussed in the previous section, we propose to leverage other GENI components to the largest extent feasible. In addition, we propose to develop as few wireless-specific devices and as little wireless-specific software as possible.

In specific, we suggest a "plug and play" approach to building specialized wireless systems, in which a common hardware / software core is augmented by specialized radios, etc., to form the various subnets. This has the following concrete implications:

- A single core hardware / software platform will be used for all "computer-like" wireless nodes (sensor nodes, urban mesh nodes, cognitive radio nodes). This platform will be based on a GENI endpoint computer, augmented with a radio API controlling multiple radio interfaces.

- Note that this platform probably cannot be used for cell-phone style devices, and perhaps not for PDAs as well. Hence the Suburban Wide Area subnet may require its own architecture and development.

- Identical wireless nodes will be used in kits, controlled experimentation facilities, and field installations. GENI wireless "kits" will consist of these nodes with GENI-supplied radios, or radios provided by researchers, in an environment created by a research team. GENI controlled experimentation environments will consist of the same equipment in a radio-controlled facility (e.g. RF shielded room). GENI field installations will consist of the same equipment installed in the field, e.g., on light poles in a city.

4.5 Provide Many Potential Upgrade Paths

Both computers and radios are currently undergoing very rapid development. Radios in particular are evolving in ways that makes the future extremely hard to predict. In addition, of course, the GENI system itself is expected to grow and change over time. Therefore it is desirable to provide as many potential upgrade paths for wireless subnets as possible.

We therefore propose to decouple the computer and radio components within a GENI wireless node, so that they may evolve separately, and so that it is as easy as possible to upgrade either the computer or its attached radio(s). The concrete implications of this approach are as follows:

- A "GENI Radio API" will form the interface between the GENI wireless node's computer and any of its attached radios.

- Wireless nodes will be designed so that they can contain multiple radios, and that a radio can be easily attached to (or removed from) an existing wireless node. Alternatively the "computer" portion of a wireless node can be upgraded without changing any of its existing radio hardware or software.

4.6 Reflect Subnet Administrative Boundaries and Concerns

GENI wireless subnets will be administered and operated, and the design of the subnets must reflect administrative boundaries and concerns. The large field installations may well be subcontracted out for "turn key" construction and management. It is also desirable that it be as easy as possible for a new installation to be fielded; for example, if a university campus or town wishes to deploy and operated its own GENI wireless subnet, it should have as few barriers to doing so as possible. At the smaller end of the scale, a researcher should be able to acquire a collection of GENI wireless nodes, and be able to operate them as desired for that research group's particular interests.

Each of these groups may have its own administrative rules, operating plans, and management tools. For example, a city-wide installation may involve management of non-wireless resources such as DSL lines, wireless backhaul links, etc. In addition, a subnet may have scheduled maintenance or upgrade intervals which must be accommodated.

We therefore propose to treat a subnet as an administrative unit, with its own administering organization and operational concerns. This approach has the following concrete implications:

- "Operations and management" is considered a distinct activity from "experimental control".

- The means by which a GENI wireless subnet is operated and managed will not be mandated by GENI-wide guidelines. An organization may do this in any way that is convenient, e.g., by employing its existing tools and network management systems. In informal laboratory setting, this function may be ad hoc or entirely absent.

- Experimental control will be carried out in a GENI-wide fashion, i.e., by the GENI Management Core.

- Any group that wishes to add its own wireless subnet to GENI will therefore employ and make available GENI wireless nodes (in standard kit form, or specially built), a GENI access router, and the GENI Management Core. They may additionally employ whatever operational management system they find convenient; this need not be made public.

5 Wireless Subnet Operations & Management

This section describes the functions and high-level implementation of the Operations & Management (O&M) subsystem for wireless subnets. Note that O&M supports internal subsystem administrative functions, and thus is quite distinct from the Experimental Control subsystem, which schedules researcher access to wireless nodes, supports the GENI Management Core functionality, etc.

The O&M subsystem is present in larger GENI wireless subnets such as field installations, but is not necessary for every GENI wireless subnet. For example, laboratory research subnets built out of GENI wireless kits may well not have any O&M subsystem. The actual O&M system is not specified in the GENI architecture so that a wireless subnet's operator can use whatever systems they find convenient. However, its interfaces to the larger GENI O&M system will be defined so that operations can be supported across the full range of the GENI system.

O&M provides operational support for the administrative organization that is planning, monitoring, and maintaining the health of a given wireless subnet. It includes such functions as facilities planning, scheduling, monitoring, and operational control; fault reporting and isolation; trouble tickets and help desks.

It is also likely that the wireless O&M subsystem will provide information to GENI researchers that will help with their research and planning, including such items as geographic maps with node locations, descriptions of node hardware and software, RF measurements and history, vehicle locations and trajectories, etc. This information and the corresponding interface is TBD.

5.1 Overview of Wireless Subnet Operations & Management

Figure 5-1 depicts the Wireless Subnet O&M subsystem within the context of an Urban Mesh subnet. This is not the only context in which O&M appears; similar functionality is also present in large-scale sensor networks and RF controlled experimentation facilities.

As shown, the O&M subsystem presents an interface to the broader GENI O&M system. This interface is not yet defined, but will likely consist of both computer-to-computer interfaces (such as automated interfaces to node schedules, trouble tickets, etc.) and human-related interfaces such as trouble-ticket escalation procedures, telephone numbers for end-to-end trouble-shooting, and so forth.

The O&M system also will likely contain an interface to GENI researchers, e.g. though a web browser, as mentioned above. This interface is not yet defined.

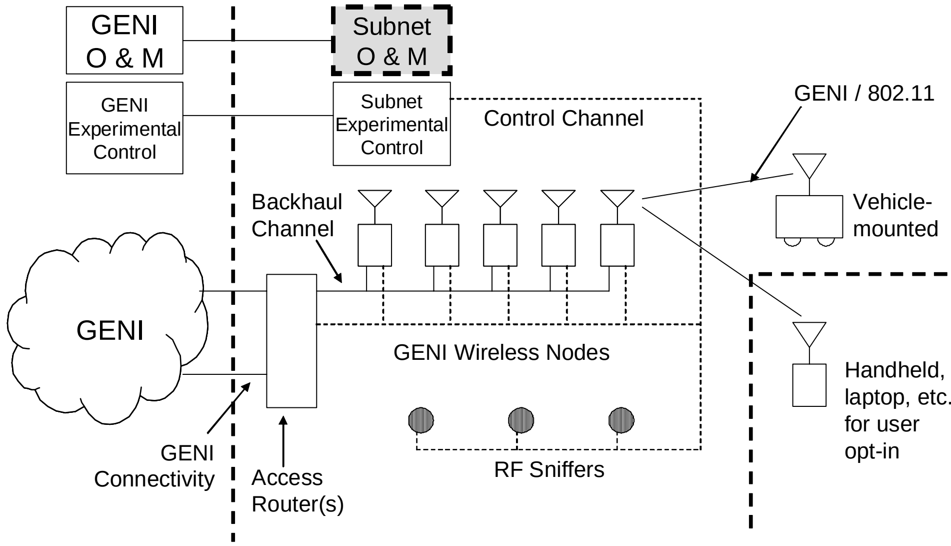

Figure 5-1. Wireless Subnet Operations & Management (in Urban Mesh context).

The O&M subsystem is designed for an administrative organization's convenience, and for that reason the GENI architecture does not specify what hardware or software will be employed.

An example may make this clear. Consider a field installation across a city that is operated by some organization. That organization may well already have its own network management system, trouble tickets, help desk, etc., and it may be easiest for them simply to fold the GENI wireless subnet management into their existing system. This is particularly true if they also need to manage other, non-GENI internal components to the subnet, such as backhaul through DSL lines or wireless links, etc. Such conventional equipment and systems do not contain GENI-defined interfaces, and are most easily managed by conventional management systems.

Since the internal details of an organization's O&M subsystem are not defined by GENI, these internals are not depicted in Figure 5-1. It is likely, however, that the O&M subsystem would have its own out-of-band management channel to those devices being monitored or managed (e.g. wireless nodes, DSL lines, etc.).

5.2 Requirements for Wireless Subnet Operations & Management

- O&M includes such functions as facilities planning, scheduling, monitoring, and operational control; fault reporting and isolation; trouble tickets and help desks.
- The exact duties or tools used for Subnet Operations & Management (O&M) are not specified by the GENI architecture; they are defined by the subnet's administrator.
- Small-scale research subnets may omit this functionality entirely.
- Major GENI wireless subnets (e.g. a field installation or RF experimentation facility) are required to provide an O&M interface to GENI O&M.

- This O&M interface will define the following kinds of information flow from the subnet to GENI O&M: current status; scheduled changes in the subnet; current and long-term RF environment for the subnet's geography, as measured by RF instrumentation; trouble tickets; help desk.

- The O&M interface will also allow researchers around the world to access information of interest, e.g., current wireless node equipment descriptions, maps, RF environment, vehicle locations and historical trajectories, etc.

5.3 External Interfaces for Wireless Subnet Operations & Management

We currently expect two different kinds of external interfaces for an O&M subsystem, as follows. Neither is specified at present.

- Interface to GENI O&M – providing a way in which the overall GENI operators can learn relevant information about the subnet's current status, projected schedules, etc., in order to perform end-to-end operations and planning support. This interface is also likely to support other operational features that must span administrative boundaries, such as help desks and trouble tickets.

- Interface to GENI researchers – providing a way in which a researcher anywhere may learn information about the wireless subnet that will be useful for planning or undertaking experiments. This is expected to include geographic maps with node laydowns, details of node hardware and software, RF measurements, vehicle locations and trajectories, etc. Possibly this will be via a web interface. (Note that this is distinct from the Experimental Control interface, which is used for scheduling and controlling GENI experiments, and for collecting experimental data.)

5.4 Hardware for Wireless Subnet Operations & Management

This hardware is not specified by GENI; it can be selected by the subnet's administrators.

5.5 Software for Wireless Subnet Operations & Management

This software is not specified by GENI; it can be selected by the subnet's administrators.

6 Wireless Subnet Experimental Control

This section describes the Experimental Control subsystem by which experiments are loaded into the wireless nodes, slivers are configured, and the resultant experimental data is collected and archived.

IMPORTANT. The relationship of this subsystem to the GENI Management Core (GMC) is unclear at present. We understand this subsystem to implement GMC for the local subnet, and to "federate" into the larger GENI experimental control structure. If possible it will run unmodified GMC software, but housed locally. (For example, if one is loading software images to 500 wireless nodes in a city, one would prefer to download the image once into the subnet experimental control, and then load it from there into the 500 nodes.) This software will need to be augmented with subnet-specific features, e.g., selection of radios to use, geographic regions, which taxis or buses should be allocated, etc.

Note that the Experimental Control subsystem for a given wireless subnet is linked into the larger, GENI-wide experimental control system so that end-to-end experiments may be set up. The interface that defines this linkage has not yet been specified.

It is currently unclear to what extent the wireless subnet's Experimental Control system will require its own software development, and how much can be leveraged from generic GENI experimental control software. Certain wireless concerns will very likely requires specialized software, however. Examples include experimental requests for certain wireless topologies, vehicle mobility patterns, etc.

6.1 Overview of Wireless Subnet Experimental Control

Figure 6-1 depicts the role of a Wireless Subnet Experimental Control subsystem within the context of an Urban Mesh. As shown, it has interfaces to both the broader GENI experimental control system and to the wireless nodes that it directly controls. We expect that this subsystem will receive allocation requests / commands from the broader GENI control, and will attempt to fulfill these obligations from the pool of wireless nodes present in the subnet.

It will be constrained in these activities by requirements imposed by an experimenter, e.g., how many RF neighbors should be present in a given topology, number of mobile nodes vs. fixed nodes, etc. These constraints clearly must be determined by a subsystem with detailed knowledge of the subnet, and thus are unlikely to be implemented by the broader GENI experimental control system.

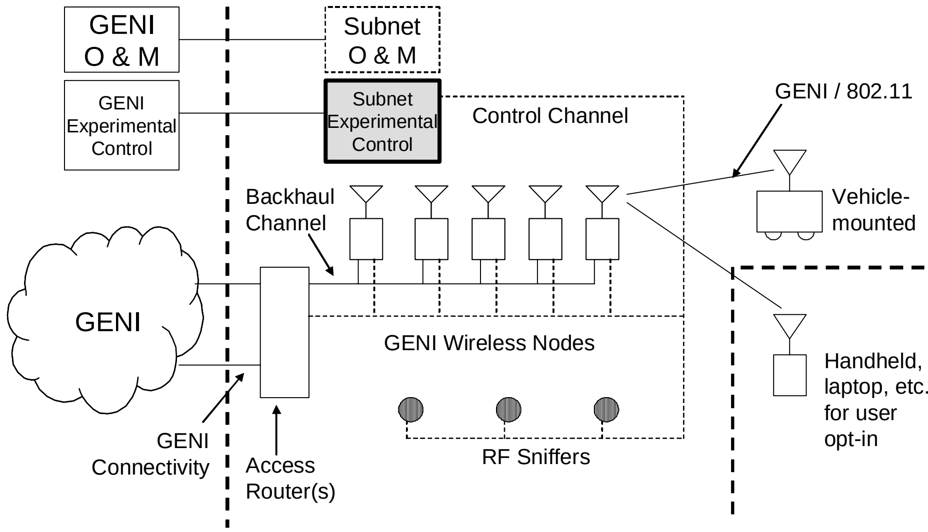

Figure 6-1. Wireless Subnet Experiment Control (in Urban Mesh context).

This subsystem is also likely to include a considerable amount of local disk storage for the following uses: storage of software images for slivers in the wireless nodes; measured data collected from experiments running within the wireless nodes; measured RF data from the RF sniffers deployed through the installation. (However it is unclear whether any measurements are actually maintained at this subsystem, and if they are, how long they are archived. See calculations below.)

A typical sequence of operations undertaken by Subnet Experimental Control is as follows:

1. Receive request (rspec) for an experiment, and determine whether it can be accommodated.

2. If so, allocate subnet resources (slivers within wireless nodes and Access Router), and obtain the relevant software images for the appropriate slivers.

3. Interact with the appropriate wireless subnodes and Access Router to create sliver, and to download the relevant software image into each sliver.

4. When all slivers are in place, send "go" signal to the slivers.

5. Collect measurement and instrumentation data from the slivers. In parallel, continue to collect RF measurements from the entire installation's RF Sniffers.

6. Store measurement data locally for archival purposes.

7. When the experiment is done, stop slivers, and free up resources.

8. At the experimenter's request, deliver measured information to the experimenter. (Should this be boiled down? Or will the whole dataset be delivered? Etc.)

Note that Experimental Control interacts with Operations & Management in the scheduling of resources. For example, there may be planned outages for the wireless nodes (e.g. for upgrades) which must be taken into account in the scheduling. As another example, O&M may contain information about mobile node scheduling that is essential for Experimental Control, such as the times at which buses are driving about vs. when they are in garages for the night.

6.2 Requirements for Wireless Subnet Experimental Control

This section provides the requirements for Experimental Control, both in terms of its major functional requirements, and in terms of sizing (specifically disk storage requirements).

6.2.1 Functionality

The Wireless Subnet Experimental Control subsystem has the following major responsibilities:

- Implement control of experiments running in the wireless subnet (wireless nodes, access router, backhaul channel allocations, archival storage)
- Perform scheduling of future experiments
- Implement GENI Management Core (GMC) functionality, including the staging of sliver software images for installation into multiple wireless nodes, halting of experiments when their time expires, collection of experimental measurements, etc.
- Implement extended control functionality for wireless-specific experimental control functions such as selection of wireless topologies, allocation of radios and RF channels, selection of moving vehicles for experiments, etc.
- Maintain archival storage of experimental results and RF measurements
- Interact with O&M subsystem in the scheduling of future experiments, and in the use of ongoing RF measurements

6.2.2 Sizing Requirements

Sizing calculations for the Wireless Subnet Experimental Control are given below. These are the first estimates for the CPU, RAM, disk, etc., requirements for the hardware needed to implement Experimental Control. They will be refined as this area is more clearly understood. Obviously the hardware sizing depends on the exact set-up, most prominently on the number of wireless nodes that need to be controlled. Therefore sizing is parameterized by those factors that drive the hardware requirements.

Sizing Parameters
N – number of wireless nodes in the subnet
Nrf – number of RF sniffers in the subnet [= N / 50]
S – mean number of slivers active in a wireless node [= 5]
R – Rate at which a sliver produces archival data (bytes/sec) [= 10 Kbyte/sec]
Rrf – Rate at which an RF sniffer produces archival data (bytes/sec) [= 1 Mbyte/sec]
I – Image download size for a user experiment sliver (bytes) [= 10 Mbyte]
Dexp – Mean experiment duration (seconds) [= 2 hours = 7200 seconds]
Darch – Time for which archival data should be stored (seconds) [= 30 days = 2,592,000 secs]

Scenario	**CPU**	**RAM**	**Disk**	**Control channel bandwidth**
Formula used	Not estimated	Not estimated	Darch * (N * S * R + Nrf * Rrf)	Down: N * S * I / Dexp
				Up: N * S * R + Nrf * Rrf
Small subnet (N = 50 nodes)	Not estimated	Not estimated	9,072,700,000,000 bytes (9,073 gigabtyes)	Down: 347,222 bytes/sec
				Up: 3,500,000 bytes / sec
Large subnet (N = 1000 nodes)	Not estimated	Not estimated	181,454,000,000,000 bytes (181,454 gigabtyes)	Down: 6,944,444 bytes/sec
				Up: 70,000,000 bytes / sec

Table 6-1. Sizing Estimates for Experimental Control (WARNING – Not yet debugged!)

Note that both the transport and storage requirements are very significant for a large subnet. We break out these numbers in more convenient formats below to emphasize how large these requirements may be. This area requires more investigation, and may perhaps require some easing in the implied requirements for transport and storage in large subnets. It is not clear whether researchers would expect to download these large datasets, perform in-situ searches and aggregation, combine them with other datasets from elsewhere across GENI, etc.

	Downstream Transfer Rate	Upstream Transfer Rate	Disks (@ 1 Terabyte each)
Large subnet (N = 1000 nodes)	56 Mbps	560 Mbps	181

Table 6-2. Sizing Estimates for Experimental Control (WARNING – Not yet debugged!)

6.3 External Interfaces for Wireless Subnet Experimental Control

Figure 6-2 provides an overview of the external interfaces for the Wireless Subnet Experimental Control subsystem. It is currently envisioned that all its interfaces are control interfaces; that is, no GENI data traffic flows through this subsystem. As such these interfaces can be implemented by any convenient transport mechanism, e.g., the Internet Protocol.

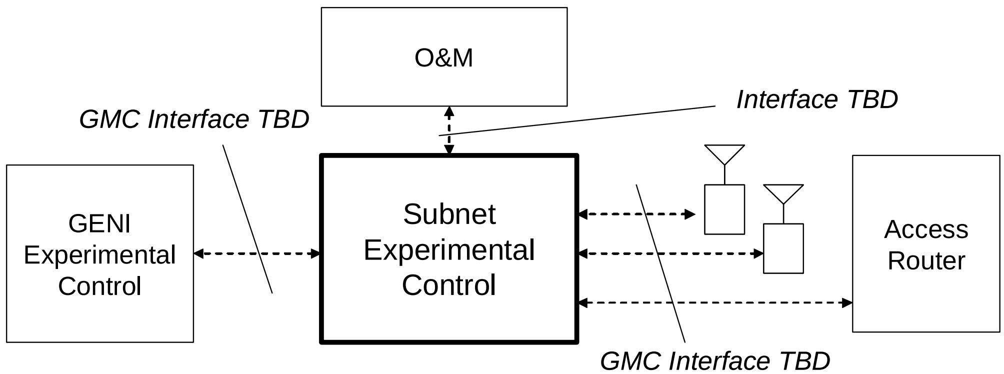

Figure 6-2. External Interfaces for Wireless Subnet Experimental Control.

There are currently no interface definitions for these interfaces, and the data requirements are at present unknown. However, Table 6-3 provides a first sketch of the types of information that are likely to flow across these interfaces.

Other Entity		**Data Flow, as Seen by Experimental Control**
GENI Experimental Control	In	Requests (rspec)
	Out	Request accepted / denied Measurement / instrumentation data
Wireless Node or Access Router	In	Measurement / instrumentation data Failure indication (software crash etc.)
	Out	Software image for sliver Sliver control information
O&M	In	Planned schedules for nodes, links, vehicles, etc. RF and geographic characteristics for wireless nodes
	Out	(? Scheduled requests ?)

Table 6-3. Sample Data Flows for External Interfaces, Wireless Subnet Experimental Control.

6.4 Hardware for Wireless Subnet Experimental Control

The hardware required for the Wireless Subnet Experimental Control subsystem is not yet clear, as both its required functionality and sizing are as yet undefined. In addition, there may be availability requirements which might require the use of redundant hardware, etc. However, at present the hardware suite appears to require something like:

- One of more CPUs of average speed
- Large archival disk storage (e.g. up to ~ 200 Terabytes), probably with backup
- Multiple network connections to wireless nodes, the broader GENI experimental control system, etc. These network connections range up to about 1 Gbps in continuous load.

6.5 Software for Wireless Subnet Experimental Control

The software required for the Wireless Subnet Experimental Control subsystem is not yet clear to the Wireless Working Group. At present we expect the following sorts of functionality will be required and appear common to other (non-wireless) parts of GENI as well; hence these kinds of functionality can probably be ported into a given wireless subnet:

- Control of experiments running in the wireless subnet (wireless nodes, access router, backhaul channel allocations, archival storage)
- Scheduling of future experiments
- Standard GENI Management Core (GMC) functionality, including the staging of sliver software images for installation into multiple wireless nodes, halting of experiments when their time expires, collection of experimental measurements, etc.

Such GENI-wide software modules will need to be augmented with wireless-specific control software, including:

- Extended control functionality for wireless-specific experimental control functions such as selection of wireless topologies, allocation of radios and RF channels, selection of moving vehicles for experiments, etc.
- Archival storage of RF measurements
- Interactions with O&M subsystem in the scheduling of future experiments, and in the use of ongoing RF measurements
- User interface to experimenters (e.g. via web browser) to view geographic laydowns, RF environment, network radio-level connectivity, vehicle trajectories, etc.

7 Wireless Subnet Access Routers

This section describes the Access Routers by which a wireless subnet is tied into the larger GENI infrastructure ("the backbone").

It is envisioned that there will be two different forms of access router – a small version for most wireless subnets, and a large version for field installations with many wireless nodes (>100 or so?). Each will have the same functionality; the only essential difference is performance and hence cost.

7.1 Overview of Wireless Subnet Access Routers

Figure 7-1 depicts the role of an Access Router within the context of an Urban Mesh. This is only one example of how access routers are used with wireless subnets; it is expected that every (connected) wireless subnet will use an access router to link the subnet into the larger GENI infrastructure.

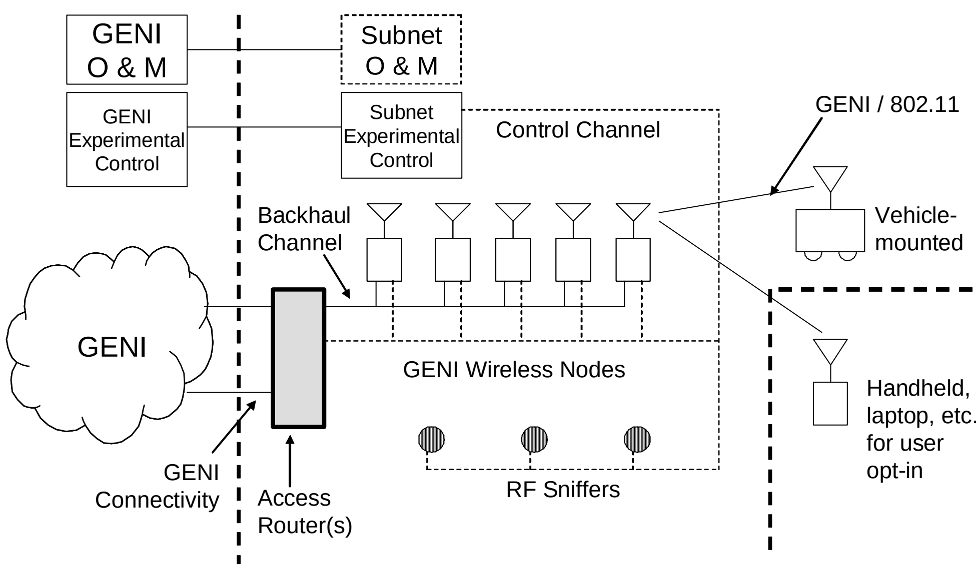

Figure 7-1. Wireless Subnet Access Router (in Urban Mesh context).

As shown, the access router provides two different kinds of GENI traffic interfaces. On one side, it connects to the main GENI infrastructure ("the backbone"). On the other, it connects to GENI wireless nodes. The access router's main job is to act as a multiplexer / demultiplexer between the shared, single backbone link and the many GENI wireless nodes.

The access router itself is a shared, sliverable resource, and its experimental use must be properly synchronized with that of the subnet's wireless nodes. To this end, the access router has a control channel interface to Experimental Control for that wireless subnet. For example, a given experiment may require allocation of 20 wireless nodes running some kind of end-to-end GENI protocols to other GENI resources somewhere else in the United States or the world. A corresponding sliver must be allocated in the access router, so that protocol units can be sent between the wireless nodes and the corresponding nodes located elsewhere in the same experiment. If some number of different experiments are running simultaneously within the subnet, each will require its own sliver in the access router.

It may make sense to “gang” several access routers when a single router cannot handle the subnet’s requirements (see below) for throughput, number of slivers, etc. This area has not yet been thought through.

It also may be desirable to “multi-home” a GENI wireless subnet into the GENI backbone, for redundancy in case of equipment or link failure. This area has not yet been thought through.

7.2 Requirements for Wireless Subnet Access Routers

- Access routers must act as full-functionality GENI routers, with slivers and virtualization as per the usual GENI router functionality.
- Access routers must be able to multiplex / demultiplex between one or more shared “backbone” channels, and as many wireless nodes as may be present within the wireless subnet. (It is expected that GENI packets will be conveyed between the wireless nodes and the access router via encapsulation in some standard format, e.g. IP or Ethernet frames, over conventional channels such as DSL lines, WiMax, cable TV, PONs, etc.)
- Access routers must be able to support the transit traffic of wireless nodes, preferably with each wireless node running at full rate. For example, if each wireless node is able to act as source or sink of a 10 Mbps flow, and there are 1,000 nodes in the subnet, the subnet’s access router must be able to support 10 Gps traffic.
- Access routers must be able support the appropriate number of slivers for a given wireless subnet without undue scheduling delay. For example, if a wireless subnet of 1,000 nodes can simultaneously support 100 experiments, the subnet’s access router(s) must be able to support 100 simultaneous slivers.
- Access routers for modest-sized wireless subnets must be very inexpensive, so that most research teams can afford them and so that there is little barrier to bringing a new wireless subnet online within GENI. For example, these routers may be conventional computers running standard GENI router software.

7.3 External Interfaces for Wireless Subnet Access Routers

Figure 7-2 presents the access router interfaces in schematic form. As shown, there are three interfaces: a backbone interface for GENI traffic; a router control interface; and a subnet interface for GENI traffic to/from wireless nodes.

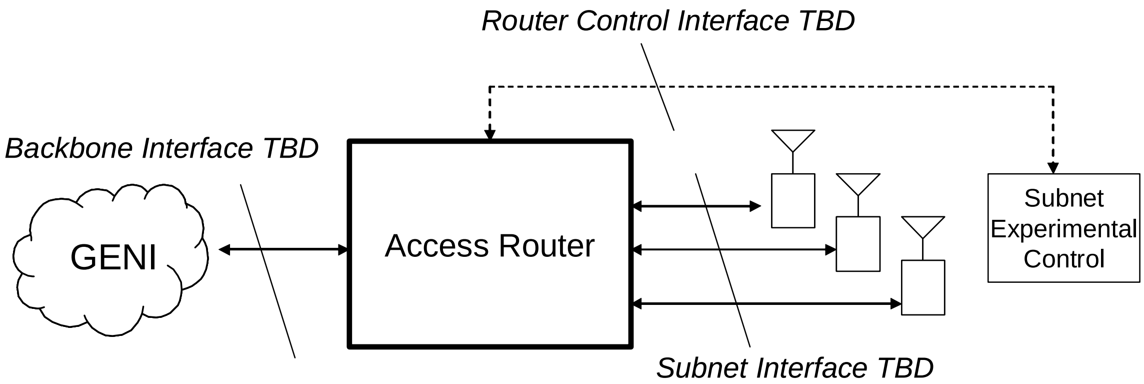

Figure 7-2. Access Router Interfaces in Schematic Form.

Interface	**Discussion**
Backbone Interface	A point-to-point interface for transporting GENI traffic packets. This interface must provide framing information that allows the multiplexing and demultiplexing of multiple slivers of GENI traffic, i.e., that maps a traffic flow to a sliver. It probably also encapsulates GENI traffic within a conventional packet and/or frame format, e.g., IP packets or Ethernet frames.
Subnet Interface	A point-to-multipoint interface for transporting GENI traffic packets. This interface must provide framing information that allows the multiplexing and demultiplexing of multiple slivers of GENI traffic, i.e., that maps a traffic flow to a sliver within an individual wireless node. It probably also encapsulates GENI traffic within a conventional packet and/or frame format, e.g., IP packets or Ethernet frames. In essence the Access Router acts as a termination point for a number of tunnels, one to each of the wireless nodes. (**Fix me**: this interface is labeled “backhaul interface” in the system diagrams.)
Router Control Interface	A control interface by which new slivers may be downloaded into the access router and initiated, slivers may be terminated, experimental data collection may be performed, etc.

It seems likely that each of these interfaces might be implemented over its own Ethernet, so that each access router would support 3 Ethernet network interfaces. Obviously many other arrangements are also possible.

7.4 Hardware for Wireless Subnet Access Routers

As discussed above, it will likely be desirable to provide two kinds of access routers for GENI wireless subnets: an inexpensive (modest performance) access router for most subnets, and a high-end (expensive) router for the larger subnets such as fielded Urban Mesh subnets. This section describes the requisite hardware for each.

The inexpensive, low-end GENI access router can probably be built from a conventional computer with three network interface cards. One will connect to the backbone link; the second will be a shared connection to the wireless nodes. The third will be a control interface to the Experiment Control subsystem, for sliver image downloads, experimental data collection, etc. In the simplest case, all interfaces will be Ethernet. The main processor and memory will run the standard GENI router software base.

To be supplied.

Figure 7-3. Notional Low-End GENI Router Hardware.

Figure 7-4 shows a notional high-end GENI router, as designed by Prof. Jon Turner. Although this hardware architecture has been designed to support a high-speed backbone router, it also appears to be a suitable hardware base for a high-end access router.

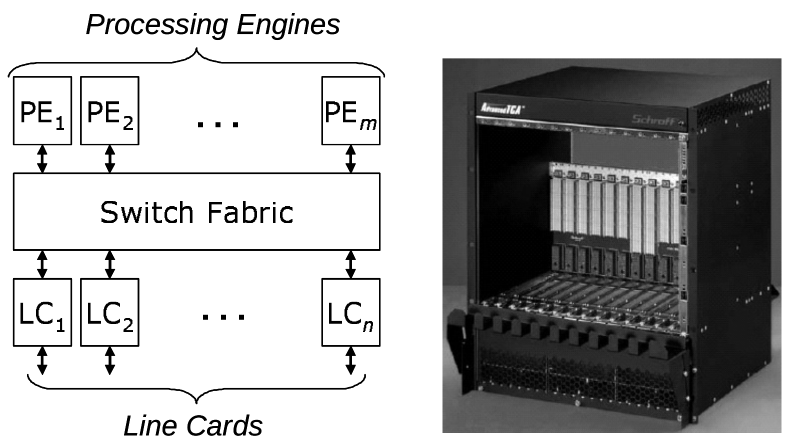

Figure 7-4. Notional High-End GENI Router Hardware, courtesy Prof. Jon Turner.

As shown, the high-end router architecture consists of a number of Line Cards (LC) and Processing Engines (PE), connected via a high-speed non-blocking switch. The Line Cards interface to channels and perform packet framing / deframing and outbound queing; they contain no researcher-provided software. The Processing Engines consist of network processors and/or field programmable gate arrays, and host the GENI slivers running experimental code from researchers.

It appears feasible to write software for one or more of the Line Cards that supports the necessary multiplex / demultiplex functionality for a GENI access router. If so, then the same hardware base can be used for GENI backbone routers and high-end access routers, i.e., the design and development work for the backbone router can be leveraged.

7.5 Software for Wireless Subnet Access Routers

This section is TBD. At first blush, though, it appears that a relatively modest software change in the planned GENI Backbone Router might turn it into an Access Router. In particular, adding new software that performs the multiplex/demultiplex function in line cards might be sufficient. (Note that this software is not currently intended to be under experimenters' control.) In essence, this new software would act as the termination of a number of "virtual" connections to the router; these connections might be implemented as IP tunnels, etc.

8 Wireless Subnet Radio Nodes

This section describes the Radio Nodes that form the core of the experimental infrastructure for the GENI Wireless Subnet.

This section proposes a baseline hardware and software design for these Radio Nodes, which can later be adapted (e.g. to larger or smaller nodes, other hardware platforms, etc.). The key design drivers for this baseline design are as follows:

- It should be very close to a conventional (embedded) computer design, so that GENI endpoint software may be adopted with little or no modification, aside from adding the requisite wireless functionality.
- It should leverage commercial "off the shelf" technology to the maximum extent compatible with its research aims, to take advantage of enormous investments in both computers and wireless technology going forward.
- It should be built with open interfaces, and these should be commercial wherever feasible (e.g. PCI-Express, USB2, IEEE 1394, etc.)
- It should accommodate a range of types of radios, including multiple radios within a single node, and make it easy to "plug in" new radios into existing wireless nodes (or alternatively upgrade the compute engines in existing nodes while keeping the current radio cards). Of particular interest, it should be possible to plug in researcher-implemented radios including high-performance cognitive radios.
- It should provide an easy "plug in" interface for a range of sensors and GPS units.
- It should have a reliable, robust control subsystem so that wireless nodes that have run amok (been hacked, had software bugs, etc.) can be brought back under control without requiring a person to be physically near the node.

8.1 Open Issues for Wireless Subnet Radio Nodes

This section contains a brief list of the open issues for wireless nodes in this draft of the System Engineering Document. These issues require thought and discussion from the Wireless Working Group before they can be resolved. Note that the subsequent sections are written as though these issues have been resolved; but this is for clarity only. In fact this document will be revised to reflect the working group's consensus going forward.

- Is one baseline design adequate for GENI Wireless? We believe the design shown in this chapter is well-suited to urban mesh, mobile ad hoc, and cognitive radio applications. It is also designed to work well for sensor network applications but is much large (bigger CPU, bus, etc) than the hardware used in most sensor network research to date.

- To what extent can unused radios be employed as RF Sniffers? This would require software development, perhaps have implications on backhaul capacity requirements, etc.

- How much data should be stored locally within a node (e.g. on a hard drive)? To what extent is this controlled by an experimenter?

- What degree of time synchronization should be mandated, or enabled, by specialized equipment on wireless nodes? For example, should they contain GPS devices, should they implement a time-synchronization protocol, and should they employ network interfaces that support timing synchronization (eg IEEE 1588)?

8.2 Overview of Wireless Subnet Radio Nodes

Figure 8-1 provides an overview of Wireless Subnet Radio Nodes within the context of a fielded Urban Mesh subnet. This type of subnet contains as many as 1,000 fixed nodes (e.g. deployed on utility poles), as well as a number of vehicle-mounted nodes as part of the experimental apparatus (e.g. deployed in buses or taxis).

Note that radio nodes appear in other kinds of subnets in addition to an Urban Mesh; this example is one illustration only. We do expect, however, that a single baseline design for radio nodes will appear in all the GENI wireless subnets and research "kits", at least in their initial deployments.

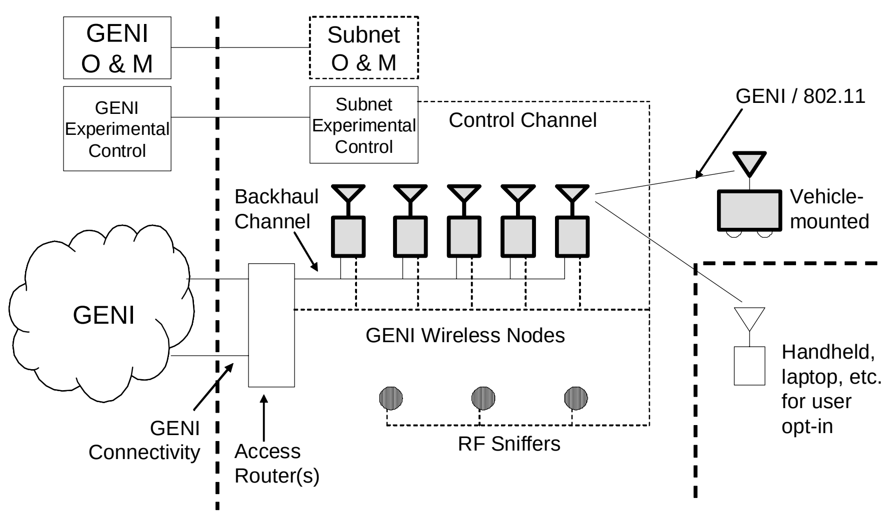

Figure 8-1. Wireless Subnet Radio Nodes (in Urban Mesh context).

8.3 Requirements for Wireless Subnet Radio Nodes

- Radio nodes must support the experimental needs of the wireless network research communities (ad hoc networks, mesh networks, sensor networks, cognitive radio networks), etc.

- Radio nodes must enable easy user "opt in" to long-running experiments on the GENI network, e.g, allow a user's laptop to connect to GENI experiments through a campus or town-wide wireless access system.

- Radio nodes must be economically available in at least the following contexts: an urban mesh installations (e.g. on street lights and within moving vehicles); sensor network deployments in labs and outdoors; research "kits" for laboratory use; and RF-controlled environments for repeatable experiments.

- Radio nodes must support the newest version of the GENI architecture (software) with the least expense and time-delay possible, as that architecture evolves.

- Radio nodes must support N > 1 slivers running within a single node, where each sliver has complete control over one or more radios.

- Radio nodes must be easily upgradeable as new radio hardware / software becomes available, and as conventional CPUs, etc., improve over time. It should be possible to "plug in" a new radio to an existing wireless node, and conversely to upgrade a node's computing resources without discarding its existing radios.

- Radio nodes must require as little human intervention as possible in their operation; for example, they must recover automatically from GENI software failures, power outages, temporary loss of connectivity, etc.

- If a radio node's transmitter begins to cause unwanted interference (e.g. by malfunction), it must be possible to shut down the transmitter without a human being physically present.

- Radio nodes must have very strong defenses against malfunctioning GENI software, slivers that have run amok, and deliberate attempts to subvert or disable the nodes.

8.4 External Interfaces for Wireless Subnet Radio Nodes

This section describes the external interfaces for a Wireless Subnet Radio Node. Because these nodes have one or more "air interfaces," i.e., can transmit and receive radio waves, they interact with much large entities than other GENI subsystems, including the Federal Communications Commission (FCC), companies that own rights to RF spectrum, and nearby interferers and primary users of the RF spectrum. These RF-related issues are so important that we break them out for separate consideration.

8.4.1 Spectrum Issues for Wireless Subnet Radio Nodes

FCC spectrum rules will govern GENI Wireless Subnet Radio Nodes. While individual research groups have sometimes performed experiments that are forbidden by FCC regulations (e.g. modified software drivers for 802.11 radios or used higher power than allowed), it is likely that the GENI network infrastructure will need to closely adhere to government regulations.

Table 8-1 presents the major possible approaches to spectrum for GENI wireless networks, with discussions as to the advantages and disadvantages of each approach. It is quite possible that certain forms of GENI wireless nodes will employ one approach, while others employ a different one. For example, Urban Mesh experiments may employ ISM band 802.11, while Suburban Wide Area experiments may employ cellular bands.

ISM Band	Advantages	Inexpensive, readily available equipment. Can use anywhere without prior agreement or license. Good bands for communication.
	Disadvantages	Potential “rising tide” interference from WiFi nets. FCC mandates fixed equipment string; this could make it hard to certify wireless nodes, especially with “plug & play” FCC mandates software driver integrity; this could make “soft MAC” approaches infeasible, and might make cognitive radio experiments impossible.
Proprietary Band (e.g. cellular band)	Advantages	Inexpensive, readily available equipment (e.g. cellphones). Little to no uncontrolled interference. Excellent bands for communication.
	Disadvantages	May be hard to impossible to gain access to valuable commercial spectrum, except in rural / remote areas.
Experimental License	Advantages	GENI gives potential for national experimental license. Could allow experimental use anywhere without prior agreement or license. Little to no uncontrolled interference.
	Disadvantages	Would need to obtain FCC license (not easy). Commercial hardware needs modification to support any experimental band.

Table 8-1. Advantages and Disadvantages of Various RF Spectrum Approaches for GENI.

8.4.2 Other External Interfaces for Wireless Subnet Radio Nodes

Figure 8-2 shows a Wireless Subnet Radio Node's external interfaces in schematic form. We distinguish "tethered" from "untethered" wireless nodes. Both have radio cards and implement a radio channel, and so are suitable for either single-hop or multi-hop radio network experimentation.

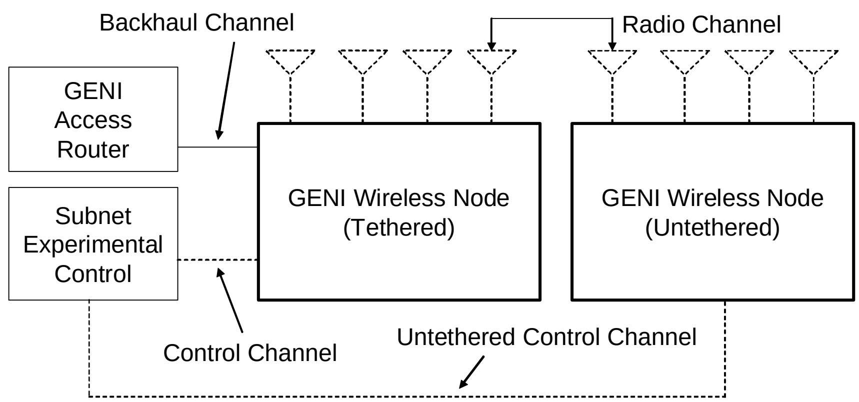

Figure 8-2. External Interfaces for Wireless Subnet Radio Nodes.

Tethered wireless nodes additionally implement two high-capacity, high-availability interfaces: a backhaul channel that carries GENI traffic and a control channel. These interfaces may be implemented by wires (e.g. DSL, PONs, etc); alternatively they may be implemented by dedicated wireless channels (e.g. WiMax). It is possible that both channels might be implemented via a single underlying connection, i.e., by logical partition of the connection. In such cases, it is required that the control channel always be fully available; that is, run-away software in the node must not be able to impair the control channel.

Untethered wireless nodes do not have high-capacity, high-availability interfaces. These types of nodes are intended for experimentation in vehicles such as taxis or buses, or in hand-held devices in the field. These nodes communicate GENI traffic only through their radio channel(s). Their control channel may be implemented by an intermittent high-capacity connectivity channel (e.g. a WiFi connection when the vehicle is in the garage), and / or by a relatively low capacity wireless channel such as cellular data schemes (GPRS, EVDO, etc). In either case, the control channel cannot be assumed to rapidly download software images for slivers, and cannot be used for high-capacity measurement data.

Interface	Discussion
Radio Channel	The RF-based communication channel between two or more GENI wireless nodes. This channel carries GENI traffic, i.e., allows communication along a GENI slice.
Backhaul Channel	High-capacity, high-availability channel between a GENI wireless node and its Access Router. This channel carries GENI traffic, i.e., allows communications along a GENI slice.

Control Channel	High-capacity, high-availability channel for Experimental Control of a wireless node. This channel is used to download software images for slivers, start and stop sliver exection, and transport measurement and instrumentation data from the wireless node to the Subnet Experimental Control subsystem.
Untethered Control Channel	A channel for Experimental Control of a wireless node that is low-capacity, or low-availability, or both. This channel is used to download software images for slivers, start and stop sliver exection, and transport measurement and instrumentation data from the wireless node to the Subnet Experimental Control subsystem.

It seems very likely that wireless nodes with Untethererd Control Channels may need to be scheduled differently from those with tethered Control Channels. For example, experiments with such nodes may need to be configured the evening before an experiment, with data harvested the subsequent evening after a day's experimentation (assuming high-capacity WiFi connectivity when a vehicle is in the garage). Such complexities must be addressed by the Subnet Experimental Control subsystem.

8.5 Hardware for Wireless Subnet Radio Nodes

The wireless network research field has been extremely fertile both in research areas and in hardware/software platforms for conducting this research. A major part of the GENI Wireless design will therefore be in the selection of hardware and software architectures to support this ongoing research within the broader GENI context. The overall GENI architecture, with its basic structure of slivers, virtualization, and experimental control, places strong requirements on this hardware architecture.

8.5.1 Existing Forms of Hardware for Wireless Network Research

We begin by reviewing several of the major, existing forms of hardware platforms that are currently being used for wireless network research. We then present a strawman hardware architecture for the GENI wireless nodes which attempts to accommodate the research needs of most of the wireless research communities within a unified, overall GENI architecture.

Figure 8-1 presents a widely used hardware platform in wireless sensor networking research, the MPR2400 / MICAz. This photograph and diagram is copyright by Crossbow Technologies, Inc., and derived from the *MPR-MIB Users Manual Revision B*, June 2006 PN: 7430-0021-07. As shown, the hardware consists of a fairly tightly integrated combination of microcontroller CPU and radio subsystem (ATMega128L and CC24240 respectively).

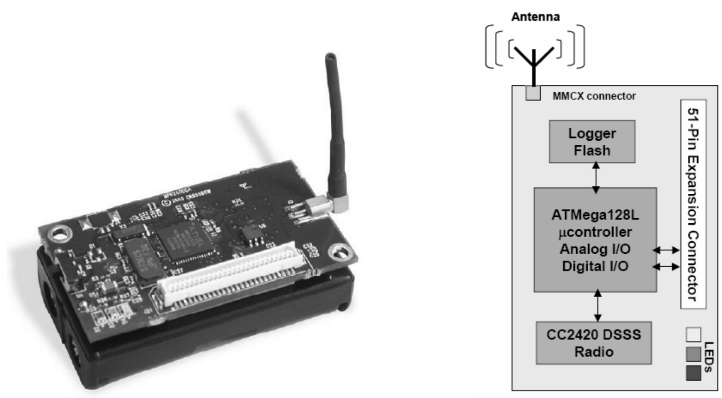

Figure 8-3. Sample Hardware Platform – Wireless Sensor Networks (© MPR2400 / MICAz).

Figure 8-4 presents a hardware architecture for wireless “ad hoc” or mesh network research, as created for the Winlab ORBIT testbed at Rutgers University. Each ORBIT Radio Node is a PC with a 1 GHz VIA C3 processor, 512 MB of RAM, 20 GB of local disk, two 1000BaseT Ethernet ports, two 802.11 a/b/g cards on a PCI bus, Bluetooth and Zigbee radios attached via USB, and a Chassis Manager to control the node. The Chassis Manager has a 10BaseT Ethernet port. The two 1000BaseT Ethernet ports are for Data and Control. The Data ports are available to the experimenter. The Control port is used to load and control the ORBIT node and collect measurements.

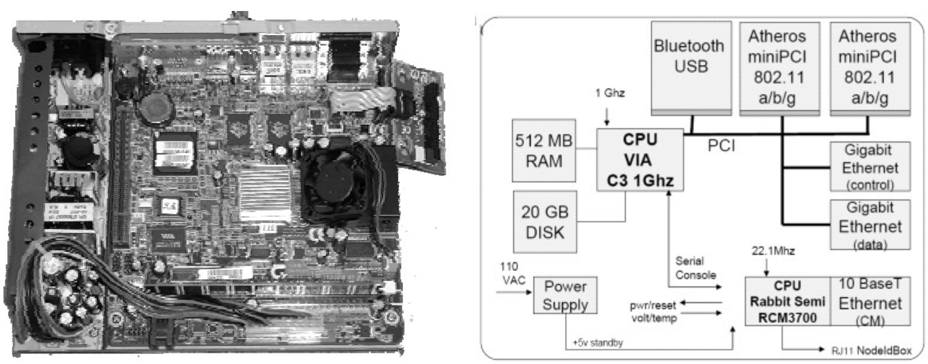

Figure 8-4. Sample Hardware Platform – Wireless Ad Hoc Networking.

Figure 8-5 shows a third hardware platform, the GNU Radio project’s Universal Software Radio Peripheral (USRP), Revision 1, developed by Matt Ettus. This platform is designed to be a low-cost research platform for experimentation with Software Defined Radios (SDRs). The USRP is designed to be used in conjunction with an external main processor (e.g. PC or Macintosh).

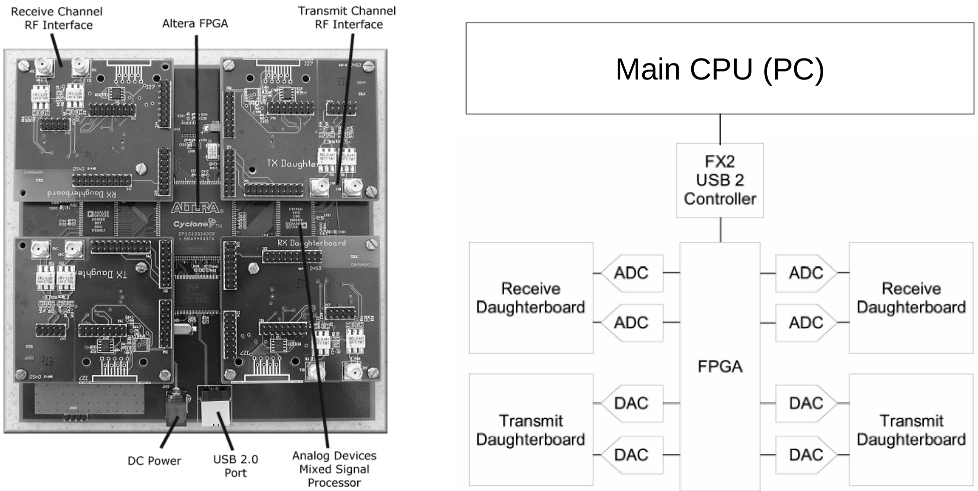

Figure 8-5. Sample Hardware Platform – Software-Defined (Cognitive) Radio.

The Rev. 1 USRP is not a particularly high-performance system, but it does provide a basic architectural approach for SDRs and (going forward) for cognitive radios as well. The major hardware features of the Rev. 1 USRP include an Altera EP1C12 Q240C8 “Cyclone” field programmable gate array (FPGA) for local control of the radio transceivers; 4 High-Speed AD Converters (64 MS/s, 12-bit Analog Devices AD9862) which can bandpass-sample signals of up to about 200 MHz, digitizing a band as wide as about 32 MHz; 4 High-Speed DA Converters (128 MS/s, 14-bit) to generate signals up to about 50 MHz (same chip as above); and daughtercards for RF transmitters or receivers.

The local FPGA is connected to the external main CPU via a Universal Serial Bus (USB 2). Since this link limits the overally system throughput, it may be replaced by a faster interface such as a PCI bus.

8.5.2 Evaluation of Existing Hardware Platforms for GENI

The preceding section briefly surveyed several major hardware architectures that are suitable for wireless networking research. As can be seen, there are major differences in these platforms. These differences are summarized in Table 8-2.

	MPR2400 / MICAz	**ORBIT**	**GNU Radio / USRP**
CPU	Micro-controller	Embedded PC	None (external)
Local RAM	Minimal	Embedded PC	External, and/or in FPGA
Radio interface	Custom-built	PCI bus	USB 2
Radio MAC	Fully programmable; implemented in Micro-controller	WiFi (802.11) in device firmware	Fully programmable; implemented in external CPU and/or USRP’s FPGA
Radio types	1 x CC2420	2 x WiFi (802.11)	4 x custom (Tx or Rx)
Sensor interfaces	Slow ADC + DAC	None	External; or could use

			daughtercard
GPS	None	None	None
Wireline interfaces	None ?	3 x Ethernet	External
Local storage	Flash	Disk	External
Power supply	Batteries	Line	Line

Table 8-2. Comparison of Existing Hardware Platforms for Wireless Research.

Since the GENI architecture is significantly different from any existing wireless network research architectures, it is not obvious that any existing hardware platform maps well onto its needs. Instead its requirements must be analyzed on their own terms, and then harmonized with the experimental requirements for the wireless networking research community.

Table 8-3 attempts to perform this high-level analysis of hardware requirements for GENI wireless nodes. Of course, it is very unlikely that "one size fits all" for GENI wireless networking hardware. Many different platform variants may need to be created. However, each variant introduces both cost and schedule risk. Thus it is desirable from a budget viewpoint to have as few variants as possible.

	Baseline GENI Requirement	**Discussion**
Main CPU	Embedded PC suitable for Xen, etc.	Must support GENI slicing & virtualization. Desirable to run identical, or near-identical, software as any other GENI endpoint, with wireless-specific additions as desired
Control CPU	Embedded PC or micro-controller	Control processor runs from ROM and/or its own flash; acts as watchdog; cannot be hijacked by hackers or runaway experiments
Local RAM	Embedded PC, large enough for multiple software images	Must be sized large enough to hold 5 (?) full images as slivers in RAM
Radio interface	PCI, Ethernet, etc.	Must support N > 1 radios in a node; must be fast enough to support high-speed radios (e.g. WiFi futures) and Cognitive Radios. Ideally would allow "plug and play" field upgrades.
Radio MAC	Fully programmable	
Radio types	Must support N > 1 radios, preferable heterogenous	Ideally would allow "plug and play" field upgrades to Cognitive Radios, new commercial radios, etc.
Sensor interfaces	TBD	TBD
GPS	Location info required; time info may be required	Required for vehicle nodes; may also be desirable for other research uses

Wireline interfaces	> 1 fast interface (Ethernet)	GENI architecture requires highspeed and highly reliable / secure control channel(s)
Local storage	Disk	Enough for multiple slivers' file systems, plus experimental data collection
Power supply	Line power; adaptors for vehicle-mounted nodes	Long-term, shared experimental infrastructure probably cannot be supported via battery power

Table 8-3. High-Level Hardware Requirements for Baseline GENI Wireless Nodes.

8.5.3 Proposed Hardware (Electronics) Baseline for Wireless Nodes

Figure 8-6 presents the proposed hardware baseline for GENI Wireless Subnet Radio Nodes. It is organized around a PCI bus with a sizeable general-purpose CPU, RAM, and disk (an embedded PC); a separate control CPU; multiple slots in which various kinds of radio cards can be plugged in to the PCI bus; and bus interfaces for sensors and GPS units.

The main goal is a flexible, open platform that is readily compatible with other GENI endpoint nodes so that very little additional software development (or porting) is required.

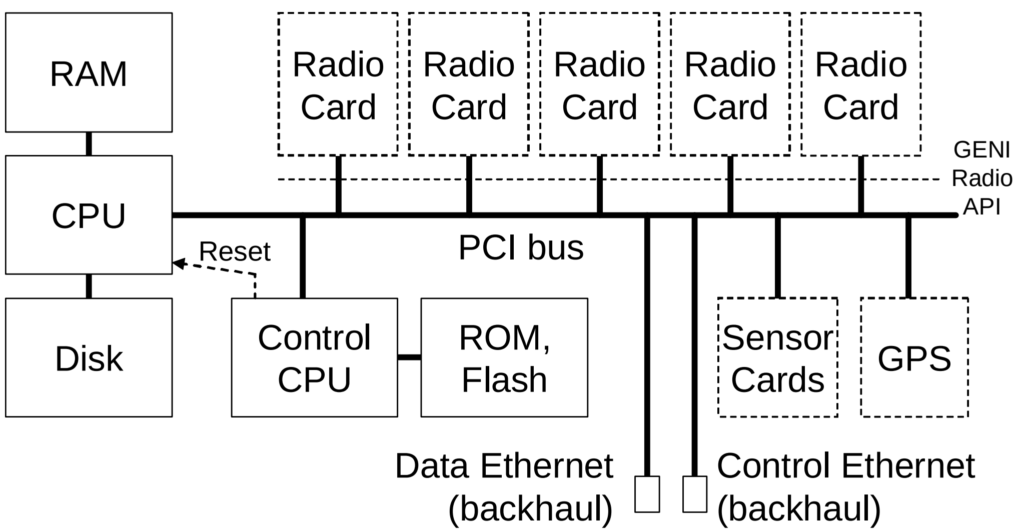

Figure 8-6. Proposed Hardware Baseline for Wireless Subnet Radio Nodes.

Main CPU, RAM, Disk. We anticipate that the CPU, RAM, and Disk will be as close as possible to those employed in other GENI endpoints to minimize the amount of software effort that will be required in extending baseline GENI software to the wireless nodes. Thus this compute subsystem should be able to directly run Xen, or whatever other virtualization technique is adopted in GENI, as well as run multiple slivers. (Note that this approach is not in close alignment with the sensor network community's general approach to date, which has emphasized small-scale, power-efficient compute subsystems).

Control CPU. The Control CPU will run specialized, trusted GENI software that loads new sliver images into the main CPU RAM, updates the GENI virtual machine software image itself, and aborts run-away software in the main CPU (whether caused by hackers or by bugs in the GENI software). This Control CPU will have a reliable, protected channel to the Wireless Subnet Operations & Management subsystem, and to the Wireless Subnet Experimental Control subsystem, which channel cannot be accessed or denied by other devices.

Radio Cards. The node will also support a number (5?) of radio interface slots on its PCI bus, each of which may be populated with a Radio Card. These radio cards may contain commercial transceivers (e.g. WiFi or WiMax), research radios such as Software Defined Radios (SDRs) or Cognitive Radios, etc. A software "GENI Radio API" will define the interface between a sliver running in the main CPU and a given Radio Card. New types of radios may be introduced into existing wireless nodes by "plug and play" of these new radio cards into an existing PCI slot, provided that the new radio card implements its side of this software API. (Although we have drawn the schematic with 5 radio card slots, in fact the Wireless Working Group believes that the baseline design should provide as many as feasible; for example, 8 radio slots would be preferable to the 5 pictured.)

Sensor Cards and GPS. The node also will support some number (TBD) of sensor devices. This part of the design is not yet thought through, but we anticipate that these sensor devices will also plug into the node's PCI bus via an interface TBD. If desired, it should also be possible to include a Global Positioning System (GPS); this interface also needs to be defined. GPS devices will be of interest in mobile (vehicular) nodes or kits used in field trials; they may also be useful in stationary nodes since they provide an accurate, synchronized time reference.

Finally, a wireless node will also contain a Data Ethernet connection and a parallel Control Ethernet connection. The Data connection may be used for wireline backhaul in large field installations; it can also be used in smaller lab deployments if desired. (A given sliver may choose to ignore the data connection if it is conducting a wireless-only experiment.) The control connection will be used for downloading new sliver software images, transporting experimental statistics back to the Experimental Control subsystem, etc. In a laboratory setting, these connections may be implemented via laboratory Ethernets. Within a campus-wide or town-wide installation, the Ethernets may be connected to any convenient backhaul channels, e.g., wireline connections such as DSL, cable, or PONs, or wireless connections such as WiMax.

The Wireless Working Group urges that the baseline wireless node be built with very high-end functionality. This will serve two important purposes. First, it makes the baseline node very flexible – e.g. it will be able to handle even very high-radio radios, processing tasks associated with cognitive radios, etc. Second, it lengthens the time before the hardware becomes so outdated that it must be abandoned. This second goal is important because wireless nodes will remain in the field, and/or in laboratories, for years before they can be replaced. Table 8-4 provides suggested implementations for hardware elements as illustrations, assuming that the baseline node were being designed today (in 2006).

Hardware Element	Suggested Implementation
Bus / interconnect	PCI Express
Network connection	1000BaseT Ethernet
Local connections	6 x USB2, plus 1 x Firewire B
RAM	4 Gbyte
Disk	300 Gbyte

Table 8-4. Suggested Hardware Elements for "Today" Version of Reference Design.

8.5.4 Packaging of Wireless Subnet Radio Nodes

Radio nodes will be used in a variety of contexts, and it is likely that several types of packages will be developed. Some of the possibilities are sketched below:

- Field deployable node, with weather-proof case, RF amplifiers, antennas, etc.
- Vehicle node, with power adaptor and external antenna mount
- Small sensor nodes, in small form factor with fewer slots, battery powered (?)

In general it is suggested that the baseline node be designed first, so that the GENI network can have wireless nodes up and running quickly and with low risk. Additional form factors and packaging can then be developed from this baseline to give a great range of research applicability.

8.6 Software for Wireless Subnet Radio Nodes

Table 8-5 outlines the major software elements in the Wireless Subnet Radio Node. This is a very preliminary outline, as much of the general GENI software architecture is not yet understood by the Wireless Working Group. As we gain a better understanding, this description will become considerably more specific.

Software	Location	Discussion
Core GENI Software	Main CPU	It is a design goal that the wireless nodes be able to adopt this software without any modification from the software suite for a typical GENI endpoint system. This software implements slivers, control and data channels, multiplexes traffic across shared links (e.g. Ethernets), provides measurement and instrumentation facilities, etc.
Radio API	Main	Requires design & implementation. Effort TBD. We anticipate that a

	CPU	sliver will be granted control of one or more radio cards, and that a given radio card will be entirely devoted to one "owner" sliver. A standard API will provide access to radio-level information such as Received Signal Strength Indication (RSSI), transmit power, etc. Some buffering must be provided to arbitrate between the sliver servicing (timesharing) and the harder realtime radio driver. This API should also abstract away the physical interconnect (PCI bus) details, so that new interconnects can be readily employed in later versions of the hardware platform.
Radio API	Radio Card	Requires design & implementation. Effort TBD. This software effort anticipates modifications to radio driver software, e.g., that software that performs MAC functionality, etc. Such software may run in processors / FPGA on the Radio Card itself; in other implementations it may be a device driver in the Main CPU.
Sensor APIs?	???	*Needs thought. Should there be open sensor APIs, or are all sensors special purpose, tailored to specific slivers, or what?*
Control Software	Control CPU	Requires design & implementation. Effort TBD. This software performs downloads of new GENI software for the Main CPU, maintains a watch on the Main CPU for processes run amok, etc. It is possible that typical GENI endpoints may also wind up with this architecture; if so, their software can be leveraged. We expect that wireless nodes will not contain trusted hardware (in the strong sense of tamper-proofing, cryptographic engines, etc.) other than whatever comes in typical commercial platforms.

Table 8-5. Major Software Elements in a Wireless Subnet Radio Node.

9 Wireless Subnet RF Instrumentation

This section will discuss RF instrumentation. Things to cover:

- Types of instrumentation, with cost points & capabilities, etc.
- Use of unused comms transceivers for instrumentation
- Timestamps etc.
- Privacy issues (capturing other ISM traffic etc)
- Software to integrate various instrumentation services into GENI
- User visualization & data exploration tools

9.1 Types of RF Instrumentation

9.2 Mapping of RF Instrumentation Types to Subnets

10 Rollup: GENI Urban Mesh Subnet

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10.1 Equipment Rollup

10.2 Example Usage Thread

11 Rollup: GENI Suburban Wide Area Subnet

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12 Rollup: GENI Cognitive Radio Subnet

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13 Rollup: GENI Application-Specific Sensor Subnets

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14 Rollup: GENI Wireless Emulation Subnets

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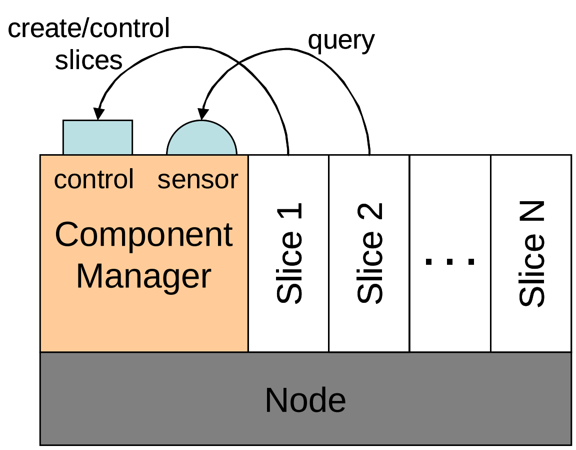

Figure 1.1: Caption + Centered + Bold (Book Antiqua 11)

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Appendix A:

Appendix B: