Technical Document on Wireless and Sensor Experiments

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GENI: Global Environment for Network Innovations

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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 is prepared by the Wireless Working Group.

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1. Introduction

The future Internet will offer ubiquitous wireless connectivity. Wireless adaptive mesh networks and embedded wireless sensor networks will proliferate at the edges of the Internet and will enable novel applications and drive architectural requirements. Accordingly, we see the facility being used to a) develop novel applications and deploy them at scale to understand what services and systems components would be required in a future Internet, and b) design, prototype, and evaluate novel architectural components and examine their performance, flexibility, and manageability. In this section, we give examples of experiments from these two categories.

2. Application Drivers

2.1 Emergency response communications with adaptive ad-hoc networks

Emerging cognitive radio technologies will be indispensable in emergency response. Consider a hurricane relief effort, with four distinct networked environments: a Command Center with extensive wired connectivity and wireless for rapid growth, an Impacted Area with all connectivity provided by wireless units deployed after the incident, a highly dynamic Evacuee Center with changing requirements met by cognitive radio deployments, and a Relief Relay Center with a quickly deployed center with mix of wired and wireless to catalog and direct relief. GENI can be used to prototype these environments. Experiments on this prototype will help analyze and develop applications suited to emergency communications that take advantage of flexible radio and network protocols to allow for tailored communication environments.

Such a prototype can, for example, be used to examine an important architectural question: does developing multiple network layer protocol implementations and associated mechanisms to allow researchers to select and utilize a particular network layer on a per application basis, over the cognitive wireless radio network, help? Such an experiment will allow networking researchers and emergency responders to evaluate communication models including multiple pre-emptible one-to-one communications and group messaging of key information, public announcements, etc. It will improve understanding of how to configure cognitive radio stacks based on the chosen communication model (one-to-one, one-to-many, bandwidth, density) as well as physical environment, and improve our understanding of how to adapt cross-layer (PHY/MAC/network) cognitive radios to changing application needs in a rapidly changing wireless environment. It will lead to software applications that can choose the most appropriate network stack based on the experimental results, given a particular application, layer 1 and layer 2 environment, and constraints/guidelines such as: best overall coverage, lowest power (preserve batteries), etc. Finally, it will lead to creation of the tools necessary to allow security and policy constraints to guide cognitive radio deployments that interact with end-to-end applications.

2.2 Participatory urban sensing

This experiment will leverage mobile devices as a platform for data gathering in cities. This will drive development of network architecture through applications that have civic and cultural significance, such as participatory urban planning, community documentation, or tracking of environmental concerns across wide urban areas. This capability might eventually expand to applications that take advantage of network privacy and integrity to support distributed medical and personal health monitoring (e.g., common, repeated tests such as glucose levels and blood pressure) and finally into first responder and other critical urban applications.

This experiment will use the GENI facility to explore new network architectural components and paradigms. For example, a privacy-preserving data sharing specification framework is essential for participatory sensing. Beyond this, an architecture of mediating access points and routers that support *selective sharing* based on privacy policies is necessary for resolution control of location and time context, provisions for operating on physical context information based on the sensor readings (adding jitter/noise to data on-the-fly to decrease resolution), and so forth. Furthermore, naming and dissemination services that respect sharing policies, and services that manage coverage estimation and sampling of these autonomous mobile nodes are examples of novel components that participatory sensing requires.

2.3 Large-Scale Sensing

Sensor networking has demonstrated great potential in many areas of scientific exploration, including environmental, geophysical, medical, and structural monitoring. GENI offers the opportunity to bridge across multiple discrete sensor networks to provide monitoring of physical phenomena at a global scale. In addition, GENI can provide the infrastructure for querying and fusing data across multiple (possibly overlapping) sensor networks in different scientific and administrative domains. A rich application domain for this infrastructure is geophysical monitoring. Examples include monitoring seismic activity along fault lines and at volcanoes, and GPS-based geodesic measurements of plate movements. The NSF EarthScope initiative is building the sensor infrastructure, and tying this source of data into GENI would enable a 'continental scale sensor network' supporting a wide range of real-time geophysical monitoring applications.

How can we architect a global-scale infrastructure for querying and fusing data from physically disparate sensor networks? To study this question, it is necessary to prototype this infrastructure, or components thereof, on the GENI facility. Challenges in doing this include developing an appropriate overlay network infrastructure for querying individual sensor data sources; constructing flows of sensor data through multiple stages of filtering, processing, correlation, and aggregation; and delivering the resulting data to the end user. Several interesting research questions arise in the context of developing this large-scale querying infrastructure, including: how to discover and address sensor data sources; design of overlay networks to support queries over high-volume streaming data; reliability and data fidelity in long-running queries subject to intermittent failures of data sources and overlay hosts; load balancing and migration of computation within the overlay network, as well as from the overlay to the underlying sensor networks; optimizations across multiple queries within the overlay, e.g., combining computation for similar sub-queries.

2.4 Transformational health-care applications in urban mesh networks

Urban mesh networks can revolutionize health care within a metropolitan area by allowing medical practitioners and support staff to remotely monitoring patients. Conversely, patients can have greater access to health-care educational resources. Such a system can greatly reduce the frequency of hospital visits, and deliver quantifiable economic benefits to the community.

An experimental prototype of this health-care mesh network will enable and test deployment of pervasive high performance wireless and understand operational issues. For example, it can help study emerging wireless standards in deployed and operational networks, examine the co-existence and interoperability with popular technologies, and deploy community advances at wireless data rates approaching 1 Gbits/s years before commodity hardware arrives. A long-running experiment can also help us collect network traces for off-line analysis.

2.5 Vehicular Networks

Vehicular networks can improve navigation safety using wireless car to car and car to curb communications to rapidly propagate unsafe road conditions, accident reports to oncoming cars, or report unsafe drivers in the proximity and imminent intersection crashes. These networks can also consume location aware resource services, and can be used as an emergency communications network. However, vehicular networks have very different characteristics from many of the other applications considered above: large scale, temporary network disconnections, correlation between motion patterns and performance, and rapidly changing connectivity to the fixed network infrastructure.

An experimental vehicular network established as part of GENI can be used to explore many architectural and research directions, such as: radio and MAC layer performance assessment (e.g., download/upload capacity at Infostations at various speeds; car to car achievable data transfers); efficient use of the multiple 802.11p channels (control and data; prioritization of channels and data, etc); coexistence of critical and infotainment traffic; network protocol design and testing, including several new network protocols (e.g., epidemic dissemination, scoped broadcast, redundant forwarding control, multi-hop routing, network coding, congestion control, etc.); and, interfacing with the Internet infrastructure (coexistence of car to car channel with Mesh, WiMAX, 3G, 4G channels, smooth handoff across the available options, and interworking with the infrastructure to obtain support in mobility management, routing, traffic control, congestion control).

3 Architectural Explorations

3.1 A Cache-and-Forward Architecture

The ubiquitous Internet architecture based on TCP/IP protocols has proved effective through a period of dramatic growth and technological change in the network, but now face a new set of challenges. Assumptions of stability and end-to-end connection have traditionally guided the design of these protocols, and have led to efficient information transfer and effective recovery strategies during periods of stress. Now, however, this end-to-end strategy is being threatened by a revolution in wireless access technology that alters dramatically the nature of internet traffic, and challenges the basic assumptions upon which its protocols were built. Where the end-points of Internet traffic were once stable and predictable, they are increasingly embodied in wireless devices, whose numbers and information rates are increasing dramatically, and which have left the stable environment of the home and office to wander in the mobile world. They have introduced instability to Internet connectivity and made the easy assumptions of end-to-end traffic flow increasingly untenable. Because the changes caused by wireless mobility are fundamental and pervasive, their solution requires comparably fundamental changes in the architecture and protocols of the future Internet.

The GENI facility could be used to explore a cache-and-forward architecture that exploits the decreasing cost and increasing capacity of storage devices to provide unified and efficient transport services to end hosts that may be wired or wireless; static, mobile, and/or intermittently disconnected; and either resource rich or poor. Fundamental to this architecture is a "transport layer" service that operates in a hop-by-hop store-and-forward manner with large files. To bring the possibilities of this architecture to realization, it is necessary to explore several research directions: reliable hop-by-hop transport of large files; classical store-and-forward transport of large files, with in network storage and reliable link layer; a Push-Pull architecture for mobile nodes, which enables opportunistic push-pull delivery of files, both to and from the wired network; enhanced naming, using which routing to and from mobile terminals will exploit location information provided by the service, and distributed caching of popular content throughout the network, making peer-to-peer file sharing a first-class service and enabling efficient reliable multicast.

3.2 Cognitive Radios

Adaptive networks of cognitive radios represent an important and interesting research opportunity for both wireless and networking communities. Perhaps for the first time in the short history of networking, cognitive radios offer the potential for organic formation of infrastructure-less collaborative network clusters with dynamic adaptation at every layer of the protocol stack including physical, link and network layers. This capability has significant implications for the design of network algorithms and protocols at both local/access network and global internetworking levels. At the local wireless network level, an important technical challenge is that of defining a control protocol framework for cross-layer collaboration between radio nodes, and then using this control information to design stable adaptive networking algorithms that are not overly complex. At the global internetworking level, ad hoc clusters of cognitive radios represent a new category of access network that need to be interfaced efficiently with the wired network infrastructure both in terms of control and data. End-to-end architectural issues of importance include naming and addressing consistent with the needs of self-organizing network clusters, as well as the definition of sufficiently aggregated control and management interfaces between cognitive radio networks and the global Internet.

Having an open-platform cognitive radio system in GENI will help the community explore a number of architectural issues towards understanding how this technology can be integrated into a future Internet architecture– these include control and management protocols, support for collaborative PHY, dynamic spectrum coordination, flexible MAC layer protocols, ad hoc group formation and cross-layer adaptation.

3.3 A New Geometric Stack

With the pervasive availability of location information, it is natural to consider if a future Internet should integrate location information into the network architecture. One experiment would be to integrate a multi-resolution distributed location service, combined with trajectory-based forwarding as a key routing primitive. The location service builds a hierarchy of servers on the location registries available in wireless networks to keep track of associated nodes. Each node is associated with a home area, so that the location-service only needs to track nodes away from home. In addition, each level stores position information at progressively lower resolution, which improves both scalability (less updates) and privacy (less sensitive information). The trajectory-based forwarding mechanisms also allows for efficient coordinate system translations at routers.

Such an experiment will provide guidance for handling location information in a future comprehensive network architecture. It may also influence the evolution of current Internet architecture. For example, geographic routing could improve manageability through smaller routing tables or the geocast concept may be incorporated into layer 2.5 designs for future vehicular networks. Similarly, the results of the location-service design may inform interested users of the possibilities of low-cost tracking services for large numbers of objects, for example at the FEMA for disaster management.

3.4 Securing the interface between wireless networks and the future global Internet

Wireless networks represent a significant point of entry for launching security attacks against the global Internet. The GENI facility can be used to understand how to secure the interface between wireless networks and the future global Internet. To do this, it will be necessary to develop experimental prototypes of adversarial nodes that can monitor wireless traffic and inject arbitrary format-compliant data into the medium. Denial-of-service attack modules will need to be developed, as will spoofing and device masquerading tools. Tools for monitoring internal buffer states at wireless nodes and wired nodes on the network will be needed to quantify the severity of denial-of-service attacks and the efficiency of packet filtering mechanisms. Cryptographic libraries will need to be implemented (starting from current publicly available libraries) in order to test various solutions. Measurements will also need to be conducted to evaluate threat severity.

These experimental systems, when used in concert, will help analyze and classify threats, including: identification of security attacks can be launched from wireless devices on each other, or on the rest of the network; differentiating between wireless and conventional threats, and developing suitable metrics to quantify the relative severity of different attack modalities on network functionality as well as on various types of applications running on users across the network. Furthermore, they will also help develop a suite of security solutions to address different classes of threats. For client-to-client threats, solutions must operate locally and might have to consider efficiency or resource issues (e.g. sensor networks). For client-to-edge infrastructure threats, asymmetric assignment of security responsibilities may be delegated to clients and infrastructure. For client-to-core threats, solutions can operate within the core itself.

3.5 Long-term Metric Collection

The GENI facility will offer a unique opportunity for data collection in a diverse set of wireless environments. When outfitted with a set of monitoring utilities, clients, access points and mesh routers within the wireless networks can provide information about the operation of deployed protocols, traffic generation, mobility and signal/connectivity characteristics. Such a set of monitoring utilities, and the resultant data sets, will have three primary purposes: (i) they will enable the researcher to obtain a comprehensive set of measurements from his/her experiment, and will prevent the researcher from needing to implement the data collection utilities his/herself, which is both error-prone and time consuming; (ii) they will provide a rich set of data from long term, operational wireless networks, such that both the basic characteristics of the wireless connectivity, as well as the general usage and operation of the network, can be comprehensively understood; and (iii) they will facilitate general operations management, and provide a means to ensure provided network functionality, such as time slicing, is operating as anticipated.

In addition the providing researchers with a comprehensive data set from their tests, this experiment will provide the opportunity to better understand the long term operation and usage of the GENI wireless facility, and will also provide better insight into general wireless network characteristics. A list of the outcomes from analysis of the data sets includes, but is not limited to understanding: traffic characteristics on the network, including packet size distributions, flow arrival rates, application frequency, and flow length distributions; the short and long term stability and/or variability of wireless links; the operation of deployed protocols, including the MAC protocol; characteristics of network routes, such as delay, jitter, and path length; the mobility patterns of mobile nodes, and the corresponding impact on application layer performance; the characteristics of the association between client devices and access points

(APs)/mesh routers (MRs), including access latency, association latency, handoff frequency, and handoff latency.