Distributed Real-time and Embedded Systems Research in the Context of GENI

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1 Executive Summary

The GENI Initiative[1] envisions the creation of new networking and distributed system architectures. Distributed real-time and embedded systems, with end-to-end Quality of Service (QoS) guarantees, represent an important class of applications for GENI. They will enable a host of innovative applications with broad societal and economic impact. This report examines the research challenges posed by real-time and embedded applications in the context of GENI.

Real-time and embedded applications include nationwide medical device and health management networks, a worldwide web of wired and wireless sensor networks, real-time transportation networks, tele-presence, and more efficient and reliable electricity generation and distribution systems. Examples of accrued benefits include remote real-time access to medical facilities, reduction in health costs and living assistance for senior and disabled citizens; reduction in traffic accidents and resulting human fatalities and injuries; minimization of traffic congestion and corresponding reduction in pollution and gas usage; monitoring and protection of critical infrastructures; reliable communications for emergency responders; prevention of cascading electricity blackouts; and the real-time monitoring and optimization of energy usage. In fact, the biggest increases in the data traffic of the future network backbone will be generated by millions of vehicles, devices and sensors spread across the world, with many of them also in motion. The GENI effort is directed toward building the networking substrate on which a variety of such applications can operate also. In order to realize the full impact of distributed real-time and embedded systems at the national level, a focused research program in this area is badly needed.

Many important real-time applications require **tight end-to-end latencies and inter-stream coordination** across wide-area networks with **integrated support for reliability, security, privacy, and certification** considerations. While the current Internet enabled the global communications and connectivity revolution, the "best effort" architecture at its core does not satisfy the integrated requirements of the next generation of envisioned real-time applications in medical, social, industrial and critical infrastructure domains. Required key features include support for end-to-end timing predictability across wired, wireless and mobile networks; co-existence of guaranteed, managed and best-effort QoS services; uniform representation of time and physical location information; quantified and measurable support for safety, reliability, availability, security and privacy; and scalability from small-scale to worldwide deployments.

We therefore make specific recommendations to (a) address the fundamental architectural limitations of the current Internet and its continued architectural erosion, (b) provide support for features required by emerging disruptive technologies and applications, and (c) ensure that the various aspects that comprise the planned GENI substrate do *not* obfuscate, and therefore fail to provide, end-to-end QoS properties. The following is an abbreviated version of the recommendations described in Section 6.

Recommendations for NSF

- **Recommendation 1: Create a New Research Program -** Sponsor a research program for the creation, analysis, experimentation, and validation of new networked real-time and

[1] http://www.nsf.gov/cise/geni/

embedded capabilities and services that seamlessly integrate the hitherto separated physical world and cyberspace.

- **Recommendation 2: Encourage Collaborative Experimental Systems Research -** Encourage collaborative research resulting in end-to-end deployment and evaluation of promising and innovative real-time and embedded applications.

- **Recommendation 3: Create a Facility -** Create a facility that would allow experimentation on a large scale and with real users and applications; and sponsor nationwide, open, shared experimental testbeds for the creation and validation of new distributed real-time and embedded system capabilities.
- **Recommendation 4: Create an Advisory Board -** Create an advisory board that includes representatives of the networking, real-time, embedded and application communities.

Recommendations for the Research Community

- **Recommendation 5: Focus on the research problems and create networking and middleware primitives –** Focus on identifying and working on eliminating the key research problems in the area and create networking level primitives and middleware, compliant with the RSIs and the recommendations of the advisory board.
- **Recommendation 6: Focus on experimental systems research and create a global repository of research artifacts.**
- **Recommendation 7: Focus on refining RSI** - Create Requirements and Service Interfaces (RSIs) that would support the collaboration among networking, computing, real-time, embedded and application communities synergistically.

Recommendations for the User Community

Recommendation 8: Active Participation - Continue active participation, contribution and collaboration.

2 Introduction

The GENI Initiative[2] envisions the creation of new networking and distributed system architectures that, for example:

- Enable the vision of pervasive computing and bridge the gap between the physical and virtual worlds by including mobile, wireless and sensor networks,
- Have built-in security and robustness,
- Include ease of operation and usability,
- Enable control and management of other critical infrastructures,
- Enable new classes of societal-level services and applications.

Security, robustness, and usability are important challenges recognized by GENI. In the networking context performance issues are often aggregated into QoS which is a multidimensional measure and not a scalar, often requiring complex specifications for applications that have strict timing and other requirements. Take the case of simple voice communication. We are concerned with not only sound quality but also availability, privacy and security. Furthermore, meeting such multidimensional QoS requirements is a system engineering challenge that demands careful and coherent design of all the layers of protocol stack and suitable interlayer operations. These aspects play a very significant role for networked real-time and embedded systems.

Networked real-time and embedded systems share many QoS concerns including end-to-end delay, jitter, safety, reliability, availability, security, privacy, usability, and cost. Different application domains, however, may give different degrees of importance to these components of QoS. For example, safety and reliability rank supreme in flight control, where cost is a key concern in voice communication. VoIP users are willing to trade lower availability for greatly reduced cost. The difference in QoS parameter specifications and requirements is the reason why automobile, avionics, manufacturing, and medical communities have developed their own networking standards.

If different application domains use shared protocols and networking standards, they must be able to specify QoS parameters as needed and obtain *a priori* assurance that the requested QoS properties will be satisfied. How to design service classes with different QoS properties on top of shared networking and computing resources is a tall order. To facilitate research, we need to create a new form of interface, the Requirement-Service-Interface (RSI) which is proposed as a means to enable the interaction between the application designers and networking service designers/providers. This can also be used at runtime as the middleware to configure optimized QoS service classes according to the application needs, subject to the constraints of networking and computing.

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[2] http://www.nsf.gov/cise/geni/

The goal of this report is to articulate the research challenges in networked real-time and embedded systems and to delineate those that should be supported by the networking substrate. We segment this goal into four sub-goals:

1. We describe a suite of new and existing applications with broad societal and economic impact. A characteristic and common aspect of these applications is that they require predictable end-to-end QoS properties in a wide-area context. Today's internet does not support these properties, and hence is a major barrier to the construction and adoption of these applications.
2. The QoS properties required by the applications we identify impose a small but critical set of requirements on a future Internet infrastructure such as the GENI network substrate. To fully support the requirements of the real-time and embedded applications, there is a need for a major research initiative that goes beyond the GENI network substrate.
3. In order to realize the promise of real-time future Internet applications, a some open technical challenges are articulated in this document. These challenges go beyond the research challenges faced by the networking layer.
4. We offer a set of recommendations to the NSF, the real-time and embedded systems research community and the end-user community.

2.1 Background

This report is primarily based on the discussions at two NSF-sponsored Workshops on "Real-Time Aspects of GENI" held in October, 2005[3] and February, 2006[4]. The workshops were part of the planning activities of the "Global Environment for Networking Innovations" program[5] sponsored by the NSF. The attendee lists for the two workshops are included in Appendices A and B, respectively. The workshop attendees included representatives from different technology domains including networking, real-time systems, and embedded systems, along with representatives of several government agencies. This report has been prepared by the authors with contributions by several others noted in the acknowledgements.

2.2 Real-Time and Embedded Systems Rationale for the Future Internet

The convergence of computing and communications gave us the Internet. This merging of technologies has impacted all aspects of society: it has fundamentally changed how corporations, governments, and individual citizens receive, manage, and deliver information and services. The basic architecture of the Internet was developed during the 1970s, and has proven remarkably adaptive over the decades, with all aspects of technology, computation, storage and communication improving by several orders of magnitude. More importantly, the basic architecture has successfully supported a wide variety of applications, including interactive browsers, global-scale information services, and bulk-data transfer and storage systems. Higher layer protocols for strong security have also been successfully layered into the internet, leading to a comprehensive suite of applications for digital commerce, secure mail, anonymous communications, and so on.

[3] http://www.mindlab.umd.edu/SNEDWorkshopOctober2005.shtml
[4] https://conferences.umiacs.umd.edu/geni/
[5] http://www.geni.net/

Despite the many revolutionary advances enabled by the Internet, there is a serious mismatch between the design of the original "best-effort" Internet protocols and the requirements of the real-time applications that are delay- and jitter-sensitive. Real-time control applications consist primarily of connection-oriented feedback loops, sensor data feeds and actuation signal streams. The performance, stability and acceptability of these applications are sensitive to loss, delay, and jitter. As a simple example, consider the following: as bandwidths and network proliferation increases, the future internet must not only support high quality video-conferencing, TV broadcasts, and voice communication, but also emerging applications such as tele-immersions with face-to-face meeting quality and tele-operations with on-site operation quality. The connection quality (reliability, end-to-end delays, and jitter) must be sufficient for large real-time control operations such as power distribution management and air traffic control to use this new infrastructure.

Currently, this mismatch between the current Internet architecture and the fundamental requirements of real-time applications has many serious implications. For example, it has forced the embedded real-time systems industry to create a number of *one-off* domain-specific protocols. Examples include:

- Factory automation and process control protocols such as PROFIBUS[6], INTERBUS[7], PLCOpen[8], and the recent Field Bus[9] standards.
- Building automation protocols such as BACnet[10], EIB/KNX[11], LonWorks[12].
- Protocols in the automotive and avionics domains, e.g. CAN[13], FlexRay[14], TTP[15], and InfiniBand[16]

The proliferation of such special-purpose real-time networking standards increases cost and creates inter-operability problems when these networks are linked together. Further, advances in sensors, wired and wireless networks, and low-power intelligent devices are enabling an entirely new class of networked applications in the sensing, monitoring and control domain.

There is also an overwhelming consensus emerging in the networking community that we need to rethink the Internet architecture from a clean slate. This is prompted by:

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[6] PROFIBUS http://www.profibus.com/

[7] INTERBUS http://www.ibsclub.com/intro/techoverview/

[8] PLCOpen http://plcopen.org/

[9] Field Bus http://www.fieldbus.org/

[10] BACNet http://www.bacnet.org/

[11] EIB/KNX http://www.konnex.org/

[12] LonWork http://www.fieldserver.com/about/lonworksprotocol.asp

[13] CAN http://www.interfacebus.com/Design_Connector_CAN.html

[14] FlexRay http://www.freescale.com/webapp/sps/site/homepage.jsp?nodeId=02WcbfNZnL3975

[15] TTP http://www.tttech.com/products/hardware/disturbancenode/summary.htm

[16]http://www.cotsjournalonline.com/pdfs/2003/10/cots10_cotsview.pdf#search=%22avionics%20networking%20standards%22

- Fundamental architectural limitations of the current Internet and continued architectural erosion that makes things worse with time;
- The inability to incorporate emerging disruptive technologies and new applications; and
- The inability to support many existing real-time applications, including the ones mentioned above, and to provide deterministic guarantees of QoS properties.

While the Internet has profoundly transformed business, services and entertainment, there is still a serious gap in the loop between the virtual world, where plans are formulated, and the physical world, where plans are executed. The goal of our research agenda in the context of real-time and embedded systems is to address the issues involved in closing this loop. The two workshops whose deliberations contributed to the core concepts of this report aimed at engaging the research and user communities to create the requirement profiles, traffic profiles, and the scientific and technological foundations needed to foster rapid convergence of computing, communication, intelligent sensing and control of our physical environment.

The next phase of technological development aims to integrate increasingly disparate aspects of our lives, at home, at work, and at play. This coming great wave, when it materializes, will profoundly change how we live. In the next section, we examine a few motivating distributed real-time applications for the future Internet.

3 Motivating Applications for Real-Time and Embedded System Domains

The GENI initiative represents a new opportunity to re-examine the networking infrastructure for systems of distributed real-time and embedded systems. To this end, the workshops' attendees took a top-down approach where we first examined a number of diverse applications that are relevant to next generation large-scale real-time networking, noting particular community specific needs and constraints.

Real-time and embedded systems can span a variety of network types, topologies and scales (e.g., ranging from next-generation local sensor/actuator networks, to large scale traffic or power grid management systems). Not only do many different systems involve significantly different networks, but a single real-time and embedded system could also span multiple networks with significantly different characteristics. A common theme of these systems is that whatever the characteristics of the networks involved, *stringent application-specific constraints must not only be enforced end-to-end by the network but also by upper layer servers including OS, middleware and the application.* Another important theme is that applications with different constraints will share the networking and upper layer physical and logical resources. How to create different service classes and ensure the proper allocation and protection of shared resources across all the layers consistently is another important challenge. Furthermore, creating the proper interfaces between the network infrastructure and the applications is an open research issues.

A typical next-generation real-time and embedded system will consist of multiple subsystems, which may be concentrated in a highly localized area (e.g., vehicle-area-networks or personal-area-networks), distributed over a wide geographic region, or may involve combinations of both local and distributed deployment. These subsystems will communicate with each other to exchange information and carry out coordinated actions. Most of the basic requirements for these environments are a consequence of the coordination needs and the degree of reliability required. As the necessary sensing and control is usually specialized toward a physical system, which has its own dynamics, the semantics of information exchange must conform to the timing and other requirements defined by the physical system. For example, reliable communication with known temporal characteristics becomes a primary requirement of such systems. When the operation of these systems has potential impacts on human health and safety, stringent certification requirements must be met as well.

In this section, we review some challenging application domains whose implementation will require research advances in the analysis, design and engineering of communication networks for distributed real-time and embedded systems. While these application domains share many concerns qualitatively, they differ greatly in their specific quality of service (QoS) requirements. For example, stringent real-time, reliability, safety, security and privacy concerns make remote surgery a distinct category of applications. The rest of this section examines each challenging application domain individually. Although the application domains considered in this section do not cover all the possible domains, we believe that they adequately cover the different research challenges that need to be addressed, which we summarize in Section 4.

3.1 Ultra Large Sensing and Actuation Networks

Problem: While many small-scale sensing testbeds exist and their characteristics are fairly well understood, very little progress has been made on investigating the design, development, operation and trouble-shooting of larger and more heterogeneous networked sensor and actuator systems. Investigation of large scale sensing and actuation systems, which are integrated as a fundamental part of the future internet infrastructure, is the next logical step in the evolution of the sensor networks discipline and is a prerequisite to successful broad-impact deployments of this technology.

NSF's investment in research to develop a new real-time and embedded networking infrastructure atop the GENI substrate would enable such a step. There is currently no good means for the research community to investigate systems challenges, bottlenecks, and research problems that emerge in larger-scale sensor and actuation networks. This is due in part to the lack of research prototypes of a sufficient size though preliminary evidence from small-scale deployments has already shown significant deviations between actual system performance and simulation-based results.

These deviations are attributed to the lack of accurate system models. Thus, the real-time and embedded networking infrastructure will not only be instrumental to applied systems research, but will also help advance basic theory and algorithms by providing, for the first time, flexible access to a larger wide-area networked system from which better models can be derived that describe realistic behavior of life-size distributed sensor and actuator systems.

Importance: There are many large-scale sensing and actuation applications which, when deployed will have far reaching impact. Examples include global weather monitoring of large and detailed sensor data sets to track micro-weather patterns, and the National Ecological

Observatory Network[17] (NEON). If new networking technologies can be developed that can ensure that timeliness, privacy, resilience to adversarial attack and other key properties are achieved, an entire generation of new applications with significant societal benefit can be realized.

One of the important applications for large and high mobility sensor networks is traffic safety. Automobiles play a large role in modern life in terms of transportation, convenience, productivity and pride of ownership. As many as 100 million vehicles are on the roads in the United States alone, with around 15 million new vehicles sold every year. However, the abundance of vehicles leads not only to congestion and waste of energy but also to serious safety challenges. In the year 2003[18], there were 6,328,000 car accidents resulting in 2.9 million injuries and 42,643 fatalities in the US[19]. The number of fatalities is roughly equal to having a commercial airliner crashing with all passengers aboard *every single day of the year*.

The basic technology building blocks needed to improve automotive safety and efficiency are already available, and appear in some new automobiles, making it possible to exploit these building blocks directly, and incurring a significant opportunity cost if they are not exploited. For example, many new vehicles from General Motors are equipped with the OnStar telematics system that has a built-in GPS receiver and an analog or digital cell-phone capability. A standard called Dedicated Short-Range Communications (DSRC) has been defined for use by automobiles for vehicle-to-vehicle and vehicle-to-infrastructure communications. Therefore, each vehicle can know not only its own position and speed but also those of neighboring vehicles, but can also be informed of road conditions such as icy spots or debris in the roadway, by nearby infrastructures or by neighboring vehicles.

Societal Impact: Pervasive and ubiquitous systems integration in such areas as home elder-care, security, and transportation will require significant development of large scale sensing, actuation, and communication capabilities across a variety of network applications. The popularity of projects such as Google Earth[20] and Microsoft's Windows Live Local[21] suggest that there is significant demand for such applications, and there could be rapid adoption and widespread use of these technologies, but only if concerns about safety, privacy, and reliability can be addressed. Developing the technologies that can create ad-hoc and dynamic networks of mobile vehicles and integrate those networks with real-time sensing, warning and automatic braking systems offer significant opportunity to avoid accidents and save lives. Applications to civil aviation, including providing up-to-date wake turbulence reports at regional airports serving increasing numbers of short-hop jets, offer further benefits to transportation safety, and thus to society at large.

Open Research Questions: Radically new network architectures may be necessary to maintain large-scale sensor networks, and to ensure that essential privacy, timeliness, and safety requirements are met. This is particularly challenging for sensor networks for auto traffic safety warning systems because of the difficult of topological controls of high speed devices. How to

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[17] http://www.neoninc.org/
[18] http://www.car-accidents.com/pages/stats.html
[19] The corresponding numbers in 2002 included 6,316,000 car accidents, 2.9 million injuries and 42,815 fatalities. Hence, the number of fatalities appears to remain fairly steady.
[20] http://earth.google.com/
[21] http://local.live.com/

ensure timing, security and other crucial properties can be defined and analyzed across heterogeneous networks whose latency, bandwidth, topology management and other semantics differ is an important research challenge. Another key challenge is to develop the technologies that can create ad-hoc and dynamic networks, which can be integrated with existing and next-generation wired and wireless networking infrastructure to create ubiquitous communication capabilities even on roadways and other highly mobile environments.

The real-time and embedded networking infrastructure to be developed atop the GENI substrate, will allow experimentation with revolutionary ideas on sensor network topology, hierarchy, configurability, protocol architecture and autonomy. This will include innovative uses of mobility (especially, but not exclusively, on the edges of networks), and exploitation of symbiotic relations between the network and its environment, such as exploiting knowledge about geographic locations and constraints on mobility to improve routing efficiency and to detect spurious alerts. Problems and solutions that emerge or become possible by virtue of scale, which cannot be realistically explored on smaller network prototypes, are likely to be identified. These systems will be subjected not only to requirements of logical correctness and cyber-constraints such as privacy and reliability, but also to physical constraints on time, space and natural resources such as energy. In this new realm, several interesting computer science challenges emerge. New models and paradigms are needed for both computation and communication, and new underlying theoretical foundations are needed to support such paradigms.

New programming languages and distributed middleware tools must be developed around the emerging abstractions. Networking protocols must be redesigned to integrate myriads of physical data sources, actuators, and computing elements. Data mining and machine learning techniques are needed to identify data patterns, learn context, and act autonomously without human assistance. Privacy and data provenance concerns must be met when handling sensitive data. Security must be assured. Correct operation must be enforced in the presence of real-time and physical space constraints. The aforementioned broad range of research directions spans most areas of computer science and collectively constitutes the challenge of building embedded networked systems that are subjected to constraints of time, space and physical laws. Such systems are likely to proliferate and to be inter-networked via nation-wide backbones. This gives rise to interesting questions regarding appropriate network architectures to support autonomy, in-network data processing, scalable information retrieval, data mining, privacy including trade-offs with data providence considerations, security, timeliness, and efficient distributed control. New networks, operating systems, and middleware are also needed, which are optimized for the new computing environment.

3.2 Distributed Rapid Response Systems

Problem: Distributed rapid response systems are essential to civilian activities, such as ensuring reliable operation of power grids or alerting and coordinating first responders to natural or manmade disasters, as well as to military command and control applications. For example, in an electrical distribution network, automatic equipment protection and switching devices must trip locally and reactively in the event of a power outage or oversupply. The lack of coordinated and timely responses from neighboring systems makes the power network vulnerable to cascading failures such as the August 2003 blackout in the US and Canada[22] and the October 2003 blackout in Europe[23].

Next-generation distributed rapid response systems, such as advanced control systems for electrical distribution networks, will involve large scale communication among control devices and monitoring stations at multiple physically dispersed locations. Because these systems will be connected by wide area networks, both cyber and physical security will be of particular importance for these systems. Because these systems will manage physical processes such as power flows dynamically, supporting their control applications will require a new body of research involving real-time dynamic topology control. Specific issues include maintaining consistent real-time views and consistent real-time actions across groups of collaborating devices; how to detect and sort out alarm storms (a common issue for networks of networked systems in general); how to eliminate duplicate alerts; etc. New research is also needed to determine the appropriate mechanisms would achieve these capabilities at the network level, which will require network/application co-design, application specified filtering actions, and appropriate interfaces between networks and applications (the definition and development of which will necessitate fine-grain interactions among the networking and real-time and embedded systems research communities).

Importance: Robust next-generation electrical networks will require communication capabilities that can support the generation of consistent, reliable, secure and timely views and coordinated control commands with timing down to the millisecond range. This will in turn enable development of "*self-healing*" processes that can minimize the formation of isolated islands of power systems, and enable rapid and safe re-integration of tripped or isolated devices. Greater information sharing among search and rescue, medical, law enforcement and reconstruction personnel could dramatically increase capabilities to respond rapidly during a natural disaster, e.g., to identify, aid and transport the most critically injured victims, to reduce looting and violence following collapse of traditional infrastructure, and to re-establish basic services as quickly as possible. According to a GAO report[24], the DOD expects next-generation command and control networks such as the envisioned Global Information Grid (GIG) to enable more timely execution of military operations, collaborative mission planning and execution, common views of the battlespace, views of a designated or target area, and more timely assessment of equipment readiness and levels of supplies available.

Societal Impact: Key issues include health and safety, economics, fairness and guarantees of availability. Because so many crucial services and infrastructures themselves depend on the power grid, the impact of greater assurance of reliable power distribution is results in an improvement in assurance for services and infrastructures that depend on the power grid. For example, improvements in command, control, and communication for first responders offer an increased ability to protect and save lives, and to minimize the disruption to society caused by natural and man-made disasters. Benefits of NSF's support for research needed to develop a new generation of real-time and embedded networking infrastructure atop the GENI substrate will also benefit the DoD and other government agencies, and collaborative use of the

[22] U.S.-Canada Power System Outage Task Force, *Final Report on the August 14th Blackout in the United States and Canada*, https://reports.energy.gov/BlackoutFinal-Web.pdf

[23] UCTE, "Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy", http://www.ucte.org/pdf/News/20040427_UCTE_IC_Final_report.pdf

[24] http://www.gao.gov/new.items/d04858.pdf

infrastructure and research products developed are likely to generate new research activities and to provide opportunities for inter-agency collaborations between NSF and DARPA, DOE, DHS, and other agencies. Historically, dynamic and collaborative research relationships involving multi-agency funding have produced a number of important technologies with far reaching impact (e.g., the modern Internet), which the proposed effort would also promote.

Open Research Questions: A key issue for networks supporting power grid control applications is to maintain consistent (and if possible, stable) views of the system through group management and topology adaptation. These issues raise significant research challenges for maintaining dynamic group structures at scale, e.g., to detect and interdict a power failure cascade that could potentially affect a significant geographic region. To support communication between power grid control stations so that they can respond in a suitably automatic and timely manner to impending or occurring hazards, new algorithms and architectures for routing, scheduling and other networking functions, which take into account the dynamics, timing constraints, locality of effects and other features of power grid control semantics must be developed. Investigations into privacy and ethics, formation and maintenance of dynamic groups, economics of insurance and reimbursement among autonomous power suppliers and distributors and applicable theories regarding global coordination for the common good in a variety of contexts, are all needed. In each of these areas, policy issues that can be encoded as doctrine *should* be enforceable and/or executable by the network – automatically -- to react more quickly than at human-in-the-loop time scales.

To support the “self-healing of power grids in the face of sabotage, accidental damage or temporary load imbalances, the real-time and embedded systems research community and networking research community also need to work with emerging technologies and standards from the power industry, such as FACTS devices[25] and Phasor Measurement Units (PMUs)[26]. Furthermore, because power grid control across independent power providers may involve personal, proprietary and/or competition sensitive information that must be protected, researchers must work with regulatory agencies to address the safety, certification, privacy and legal issues that arise in this domain.

Common issues across civilian and military command and control application domains include mobility, imprecise information, clock synchronization and remote actuation of safety and control interlocks. For example, situational granting and revocation of control authority dynamically and at scale in heterogeneous networked first-responder systems will require new kinds of interlocks involving network-level mediation of control authority.

3.3 Tele-presence

Problem: In the 21st century, the technological landscape continues to change rapidly. Looking ahead, we face many challenges that are of the highest importance. For example, we are now facing the rapid depletion of natural resources, especially oil. In addition, our population is rapidly aging and few senior citizens will be able to afford nursing homes. Furthermore, the very world we are living in is deteriorating: global warming and pollution threatens the future of mankind.

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[25] IEEE Power Engineering Society FACTS Application Task Force, *FACTS Applications*, IEEE Publication 96TP116-0, 1996.

[26] http://www.energy.ca.gov/pier/final_project_reports/600-00-019.html

Importance: These challenges, while seemingly diverse, in fact have a common theme. As was first articulated by Adam Smith, economic growth is rooted in the increasing specialization and collaboration in production, service and the creation of knowledge. As technologies become increasingly more complex, so does the web of inter-dependency between specialized forms of production, services and knowledge creation. Urbanization was the industrial age's solution for the need for close collaboration. However, there is a limitation of how many people can crowd into small spaces effectively and sustainably. Traffic congestion, pollution and wasteful use of energy and time due to the need to transport people to and from work are already taxing the lives of many people in modern mega-cities.

Societal Impact: We need a better solution to meet the grand challenge in economic growth: how to support the ever-increasing need of specialization-and-collaboration, without crowding increasingly more people into tiny spaces. A promising solution approach is to provide ubiquitous real-time tele-operation and tele-immersion capabilities that allow human beings to transcend the space in which they are located. The benefits will be history making.

Ubiquitous real-time tele-operations and tele-interactions would eliminate much work-related travel, and with it the dreaded traffic jams that waste energy, pollute the air and waste our time. These technologies would also open the door to allowing relatively healthy seniors to stay at home with various degrees of remotely orchestrated living assistance. This would improve the quality of their lives and would save great sums of money as compared with sending them to nursing homes. It also would allow expert surgeons and physicians to provide their services effectively around the country for other purposes, such as improving health care in underserved areas.

Currently, productive collaboration in research, development and education still depends heavily on face-to-face interactions. However, the scope of face-to-face interaction is self-limiting as participants' geographic locations and schedules diverge. Ubiquitous and high fidelity tele-interaction / immersion and tele-operation technologies can greatly narrow these differences and allow for unprecedented scope in collaboration in research, development and education. The recent experience in the United States with outsourcing services to far away places such as India, in many cases resulting in improved service at lower cost, is only the initial evidence of the effectiveness of this approach.

Local public safety officials face flat or shrinking operations budgets, which limit their ability to add personnel and resources. More than ever before, these local officials and members of border patrols, and emergency management agencies such as FEMA are looking for ways to work smarter, faster and safer, . A ubiquitous and high fidelity real-time spatial-temporal information systems supported by sensor networks would allow more effective monitoring and precision dispatching of policy and emergency personnel. Tele-operations would also help reduce the number of people needed to perform these activities, and would help them to stay out of harm's way.

Open Research Questions: Tele-operation are high-end applications for networked systems. Future tele-operations require precise and reliable real-time and jitter controls. The network, middleware and application must support consistent views and consistent actions in real-time for each group of distributed users with specified latency and latency jitter bounds. If the operation is safety related, it must be certifiably safe and reliable. Future tele-operations require precise and reliable control over latency and latency jitter. Future tele-immersive environments will consist of many 3D cameras capturing multiple views of participants in several rooms, rendering all views together, and therefore contributing to creating a 4D video presence among tele-conference participants. The future 4D high-fidelity tele-presence environment will have visual information that includes RGB information, depth information in each view and multiple views of each object. The ultimate goal is to have up to 100 cameras in 360 degrees circle around the room capturing full body vision of tele-presence participants.

Ensuring that the capture, transmission, processing, and display of information maintains high fidelity real-time characteristics across a variety of distributed sources and destinations, will require significant new advances in distributed (and potentially content-aware) scheduling, network and end-system co-design, and real-time routing and signaling. There are currently a number of available infrastructures with which these new research agendas could be pursued[27, 28, 29, 30, 31]. Tele-immersion applications routinely use 10 Gb/sec bandwidth – an important research question is whether they can obtain *n* Gb/sec "slices" from the GENI substrate, with a configurable topology so that they can then use their own protocols for high performance applications.

Together, tele-operation and tele-immersion demand new thinking in architecture design, ranging from a historical best effort approach to radically new architecture substrates that will not only support best effort applications but also high-performance and high precision designs. The GENI facility should support such experimentation.

3.4 Networked Medical Device and Health Management Systems

Problem – Medical Device Systems: Next generation networked medical device and health management systems are envisioned to be ubiquitous systems of networked systems for secure, reliable, privacy-preserving, cost-effective and personalized quality health care, leading not only to better health-care delivery, but also to improving people's quality of life in general. Unfortunately, current medical devices are still mostly standalone subsystems with proprietary designs. Medical workers often need to manually transfer data among several machines. They must mentally correlate many paper records and screen displays from different diagnostic and monitoring machines. Sometimes, they also need to set different devices manually, to emulate the interlocks needed between different devices and actions. This is a time consuming, burdensome and error prone process, and when a medical worker's attention is distracted, tragedies may occur. For example:

> *"A 32-year-old woman was having a laparoscopic cholecystectomy performed under general anesthesia. During that procedure and at the surgeon's request, a plain film x-ray was shot during a cholangiogram. The anesthesiologist stopped the ventilator for the x-ray. The x-ray technician was unable to remove the film because of its position beneath the table. The anesthesiologist attempted to help the technician, but found it difficult because the gears on the table had jammed. Finally, the x-ray*

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[27] http://cairo.cs.uiuc.edu/teleimmersion
[28] http://www.cs.unc.edu/Research/stc/projects.html
[29] http://www.engadget.com/2006/06/01/hp-coliseum-does-web-conferencing-in-3d
[30] http://www.evl.uic.edu/core.php?mod=9&type=6&cat=28
[31] http://www.gatech.edu/innovations/futurehome/

was removed, and the surgical procedure recommenced. At some point, the anesthesiologist glanced at the EKG and noticed severe bradycardia. He realized he had never restarted the ventilator. This patient ultimately died." APSF Newsletter, Winter 2005.

Problem – Elder Care: The aging of baby boomers is creating social and economical challenges. In the United States alone, the number of people over age 65 is expected to hit 70 million by 2030, doubling from 35 million in 2000, Expenditures in the United States for health-care will grow to 15.9% of the GDP ($2.6 trillion) by 2010 (Digital 4Sight's Healthcare Industry Study) as a result of the accumulative impact of chronic degenerative diseases in the elderly and their increasing dependence on the health care system. Unless the cost of health care for the elderly can be significantly reduced, our financially stressed Social Security and Medicare/Medicaid systems will be bankrupt. A major cost is the loss of ability to remain in the home because of the need for greater health care supervision. Advances in sensing, object localization, event monitoring, wireless communications technologies make possible the unobtrusive supervision of basic needs of frail elderly and thereby replicate services of on-site health care providers. It is postulated that implementation of a cost-effective, reliable, secure and open personal assistance system that provides real-time interaction between elderly people and remote care providers can reduce their hospitalizations and transfers to skilled nursing facilities and improve the quality of their lives by preserving independence.

There are, however, several challenges that must be tackled in order to leverage rapid technology advances in sensing devices, computing, database, middleware and wireless networking for building such an assisted living infrastructure. First, the issue of building an open, user-friendly environment with well-defined abstract interfaces has to be adequately resolved so as to allow new hardware/software components of different vendors to be incorporated into the system. Second, the cost of installing and maintaining such an infrastructure has to be kept low so as not to defeat our intention of reducing health care expenditures. Third, system robustness and reliability have to be ensured and critical services should not be compromised in a constantly evolving system. Last but not least, in spite of the fact that there are many forms of workload dynamics ranging from web-browsing, audio/video data streams and database transactions to time-critical, multimedia streams which support tele-medicine; different forms of QoS must be provided, at different levels, to applications subject to the constraint of never interfering with or compromising critical services.

Need	% of Residents With Need	% of Residents as Primary Cause
Needs prompting to take medications	95	42
Risk of injury due to falls	42	17
Unable to get up after a fall	20	17
Monitoring of vital signs too labor intensive	12	20
Needs physical assistance with Activities of Daily Living	90	67
Incontinent, patient/care-giver can't manage soiled garments	62	50
Needs prompting to toilet on a schedule	67	17
Needs prompting to go to meals	33	10
Needs prompting to bathe	75	0
Gets lost in apartment	17	0
May wander out of facility	12	10
Needs monitoring of blood sugar frequently	20	8
Needs monitoring of weight daily/weekly	25	0

Table 1: Factors contributing to the loss of independence and institutionalization

Importance: To understand the factors contributing to the loss of independence and institutionalization, a survey was conducted of health care providers of frail older adults at Washington University in Saint Louis. Results of the survey are provided in Table 1. As shown, many factors that contribute to the loss of independence can be substantially mitigated through deployment of the aforementioned infrastructure and provisioning of services such as time-based reminders of daily activities, non-intrusive monitoring of physiological functions, fall detection and response, and real-time communications with remote care providers. Representative populations that will benefit from the infrastructure include elderly people who are home-bound and physically challenged. Such patients would include those with severe arthritis, hemi-pelagic strokes, O_2 dependent COPD, and frailty that compromise their use of transportation. A second representative group will be individuals who have cognitive impairment and require daily supervision in the performance of daily activities (e.g., taking medicine, preparing meals) but live alone or without a responsible caregiver. In both groups, physiologic parameters critical to the medical maintenance of residents will be monitored; for example, blood glucose in the management of diabetes, daily body weights in the management of congestive heart failure, O_2 saturation in the management of pulmonary disease, blood pressure in the management of hypertension. Falls can also be monitored as they are often the first sign of an acute illness such as pneumonia, urinary tract infection and medication toxicity[32], or chronic conditions such as vitamin D deficiency, postural hypotension, and a seizure disorder[33] [34] [35]. Should such a wireless-based software infrastructure exist to help these representative populations to maintain their capability of independent living, a major potential financial saving in senior care will result. From a social perspective, such an infrastructure not only increases the ability of elder people to live independently, but the opportunity to remain at home and in contact with their social network and support system[36]. The latter has its advantages that go beyond patient satisfaction[37].

Societal Impact: Medical procedures and elder care are very expensive and many of our citizens have difficulty affording it. To reduce the costs of these crucial services, we must significantly improve the productivity of medical service and elder care by automating the labor-intensive process. Furthermore, the quality of medical service and elder care can be improved by eliminating many manual and error prone procedures. As we connect systems

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[32] Vassallo M, Sharma JC. Incidence and prognostic implications of falls associated with acute medical illness: a medical in-patient study. Int J Clin Pract. 1998:52:233-5

[33] Bischoff-Ferrari HA, Orav EJ, Dawson-Hughes B. Effect of cholecalciferol plus calcium on falling in ambulatory older men and women: a 3-year randomized controlled trial. Arch Int Med. 2006;166:424-30.

[34] Campbell AJ, Borrie MJ, Spears GF. Risk factors for falls in a community-based prospective study of people 70 years and older. J Gerontol Med Sci 1989;44:M112-7.

[35] Vellas BJ, Wayne SJ, Garry PJ et al. A two-year longitudinal study of falls in 482 community-dwelling elderly adults. J Gerontol A Med Sci 1998;53A:M264-74.

[36] Kane RL. The long and short of long-term care. In Cassel CK ed. Geriatric Medicine: An evidenced-based approach. 4th ed. NY Springer; 2002:99-111.

[37] Barrera m. Models of social support and life stress: beyond the buffering hypothesis. In Cohen l. ed. Life events and psychological function: Theoretical and methodological issues. Beverly Hills, CA Sage 1988.

with different degrees of criticality together and let them share resources, the development of a certifiably safe infrastructure is a long term R&D goal that must involve advanced technologies and legally sound certification processes. We need a scalable, reliable, and secure large-scale real-time architecture for pervasive health monitoring and medical procedures at home, in hospitals and emergency rooms and on battlefields. In addition, we need reliable closed loop therapeutic support for tele-surgery and anesthesia with stringent real-time requirements such that closed loops can operate in kHz time scales, and with very high degrees of reliability. Another important aspect is elder care as the number of people requiring such care increases in the coming decades. Medical monitoring applications and many other systems for elder care have similar requirements for timing and reliability, but may have much larger scalability needs due to the size of the patient population involved.

Open Research Questions: Networked medical device systems and assisted living systems share many similar QoS concerns with other applications, including real-time, reliability, safety, security and privacy. However, safety and reliability requirements are stringent and certification is needed whenever safety is an issue. This requires an architecture that is fundamentally different from the traditional "best effort" design approach. Instead, we need a new networking architecture that is designed from ground up to support verifiable real-time, reliability and safety properties. This, in turn, demands strong isolation primitives, requirement traceability in the design process and instrumentation and built-in support for fault injection tests. GENI facility needs to support experimentation of not only best effort architecture designs but also high confidence designs.

From a system engineering perspective, high confidence real-time middleware architectures must be designed to complement high confidence real-time networks. These middleware architectures must create new abstractions for the deployment of safety interlocks and other mechanisms for enforcing distributed real-time, fault-tolerance, security and reliability concerns of these systems. In addition, these middleware architectures need to support high-fidelity configuration of shared networking and computing resources into service classes with different QoS attributes for different application domains, based on a common and reusable networking and end-system infrastructure.

Connecting devices and information systems with different levels of criticality, isolation and protection requirements pose a significant research challenge. Basic extensions to theory are needed to understand how networks can provide rigorous, robust and detailed "per interaction" assurances of timing, criticality preservation, isolation, protection and other crucial properties. Imprecise, partial or delayed information, and other features of real-world networks must be taken into consideration, and new techniques must be developed to reduce the imprecision, incompleteness and delay in providing information throughout the network. For example, if alarm storms can be addressed in a variety of ways, e.g., by providing sufficient networking resources to handle the storm, by detecting and filtering alarm storm traffic, and/or providing flow control and other mechanisms to maintain isolation of critical traffic, then engineering principles to determine which combinations of these techniques should be applied under various circumstances will be needed.

An essential feature of the networking architectures needed for next generation networked medical device and health management systems, is that devices configured for particular applications, e.g., for in-home care[38] will need to coordinate across wireless LANs[39] due either to inaccessibility of other networking infrastructure (e.g., in remote search and rescue or military operations) or by design (e.g., to increase the efficiency of surgical teams and to reduce the potential for error in dynamic operating room environments). Furthermore, in applications such as automated patient monitoring and care, the patient's physiological responses must be sensed, considered in control decisions and manipulated by actuators. The network QoS attributes must be parameterized with patient specific data and the QoS attributes must be ensured by the system.

Ensuring security at various levels and protecting medical/personal data in a privacy-preserving manner is also essential in wireless-enabled medical LAN/WANs for health care. Because wireless networking will be the predominant communication medium, security mechanisms and its well-designed interfaces must be built in the network, its protocol stack and its APIs. Also, medical and personal data should be protected with different levels of information disclosure to different persons (healthcare providers, medical team, and relatives). A rigorous framework for interoperability and its corresponding security architecture to support security and privacy in a wide range of operational contexts must be established to protect information confidentiality, ensure data integrity with link-level authentication and encryption; and allow access of medical data according to their role in the patient's life.

How to ensure reliability, timing and other crucial system properties is especially challenging when interfacing with and utilizing the increasingly more powerful (and more popular) wireless technologies. Consideration of how the devices interact within a LAN, how timing and other properties can be assured, and how the specific local and remote interactions among different combinations of devices will impact network properties such as congestion, will require significant additional study. The potential sensitivity of applications to the particular slices of network resources allocated to them motivates careful attention to how those slices can be defined and enforced. To allow such slicing to be done efficiently and with high assurance that system level properties, such as timing and reliability, can be realized, new research is needed into how networks, middleware and operating systems can support end-to-end composition of heterogeneous QoS concerns for these highly diverse classes of networked medical device and health management systems.

3.5 Summary of Motivation for NSF Funding

The application domains listed in this section strongly motivate significant NSF investment in the development of real-time and embedded networking infrastructures where collaborative research and development between the real-time and networking research communities can be conducted. For example, large scale sensor and actuator networks may lead to societal changes due to integration of computing and communication with the physical world, in the same sense that the Internet brought about a fundamental transformation in human communication. Recent years have seen a dramatic increase in research activity in this area, evidenced, for example, by the emergence of sensor networks as an increasingly important subfield of

[38] Stankovic et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges", HCMDSS Workshop, Philadelphia, PA, June 2005, http://www.cis.upenn.edu/hcmdss/Papers/submissions/13.doc

[39] "Medical Device Plug and Play Interoperability Program", http://mdpnp.org/Home_Page.html

computer science with its own conferences, journals and NSF programs. Managing nomadic connections between mobile ad hoc nodes and wired or wireless fixed infrastructure will give new insights into how networks at different scales, and with different load and timing characteristics, can be coordinated to achieve timing, privacy protection, criticality isolation and other essential system properties end-to-end.

Distributed rapid response systems for such applications as electrical power distribution constitute another crucial domain, especially due to the significant extent to which other technologies and services rely on them, and due to the compelling research issues raised by areas such as prevention, detection, and interdiction of cascading failures, which also have implications for managing failure cascades in other application domains. Emergency first responder systems also provide significant opportunities for inter-agency technology transition and potential for coordinated research sponsorship and collaboration (e.g., with DOD, DOE, DHS, and NIH).

Tele-presence applications offer further motivation for NSF investment in real-time and embedded networking infrastructure, and in research using that infrastructure. Currently, tele-operations are actively pursued by many research labs. The Haptic Community website[40] provides links to them. From the perspective of high performance tele-operations[41], a key issue is the creation of an integrated backbone and edge networks including mobile networks with voice, image, sensor and actuation interfaces, which are supported by QoS-managed middleware and operating systems. Creating the networks and the upper level system infrastructures that will allow users to carry out tele-operations and tele-immersion securely, reliably and safely is the challenge. For example, remote surgery across hundreds of miles is technically possible today but safety concerns (particularly involving the current internet) may stop the idea cold. Neither do we have confidence in relying on today's Internet to manage and control electrical power distribution or to conduct air-traffic control. To do that we need to support the necessary science and technology advances to allow for the effective and rigorously enforced overlay of virtual infrastructures with different QoS requirements onto the same physical infrastructure.

Finally, in the domain of networked medical device and health management systems, the impending crisis in providing suitable elder care as the baby boom generation ages means that real-time and embedded networking infrastructure and research be focused in areas including technologies for assisted living. Also, privacy, security and reliability issues related to the direct use of personal information within distributed automated healthcare systems should be addressed.

Common lessons from these application domains include the need to represent time and spatial position explicitly within the network infrastructure and the underlying GENI substrate; the need for guarantees at multiple time scales and a common view of time at various locations; the need to manage groups/topology dynamically and at scale within the network infrastructure; and the need for applications and the network infrastructure to interact at a fine granularity. An investment in infrastructure to support distributed embedded and real-time systems networking research to meet these needs is therefore most timely and appropriate.

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[40] http://haptic.mech.northwestern.edu/PaperArchives.html

[41] See http://www.telepresence.org/ for more tele-presence applications

4. Research Challenges

The GENI facility has the potential to be a significant enabler for investigating a myriad of the real-time and embedded systems challenges articulated in this section. New protocols and services will be designed that utilize the basic GENI substrate, expanding the set of network capabilities in ways that provide greater utility to the real-time and embedded systems applications outlined above. Fundamentally, the basic GENI substrate will be leveraged to catalyze basic end-to-end research on supporting real-time requirements and predictability. Researchers pursuing higher-level real-time and embedded systems services will have opportunities to design and investigate new services for these systems, enabled by the new networking stack, that are more suitable for real-time and embedded systems. The GENI substrate will thus give rise to a major research undertaking at the intersection of networking research and research in embedded and real-time computing.

In this section, we outline the important attributes for systems of networked real-time embedded devices and discuss how to create the proper primitives at the appropriate levels of abstraction that would allow composing different QoS services to meet various requirements. We note that the applications identified here are complex systems of networked systems and the communications must integrate harmoniously with all the other components of the system.

Support for many of the important attributes for distributed real-time and embedded applications is inadequate at present, particularly in how the protocols with specific attributes interact with each other and how such interactions impact the attributes. Such attributes include timeliness, reliability, robustness, stability, security, privacy, scalability and safety. While their individual values are domain specific and technology dependent, their representation and protocols must be consistent across core and edge, and wired and wireless networks.

4.1 Uniform Representation of Time and Physical Location

The proper coordination of a system of networked systems requires a common view of time and location. This leads to a basic requirement of having a common representation of time and location along with the means of acquiring this knowledge by diverse systems. For time, a common representation has to be developed and standardized with sufficient resolution to handle clocks of various speeds that may be deployed in various systems. In addition, the clocks at all active nodes in the system have to be synchronized to a sufficient degree. At present, on the Internet, the primary means of clock synchronization is the NTP[42] protocol which can yield synchronization to within a few milliseconds. This level of synchronization is insufficient for many real-time and embedded applications. We need to develop new mechanisms for achieving higher degrees of clock synchronization without requiring the widespread use of expensive mechanisms such as atomic clocks. Such mechanisms may therefore need to sit closer to the hardware in order, for example, to have control over timestamps created at actual packet transmission times. The development of IEEE 1588 for high precision clock synchronization is an important development in this area[43].

[42] D. L. Mills, "RFC 958 - Network Time Protocol (NTP)," September 1985.
[43] http://ieee1588.nist.gov/IEEE%201588%20Agenda/eidson-TandM.pdf

Similarly, we need to develop and standardize a common representation for location information. Typically, we can use the longitude, latitude system with the third dimension as the height from the mean sea level when a global position is required. We may also require a means of representing a local, relative coordinate system for which we may be able to use a simpler set of dimensions (e.g., to indicate pre-defined regions in an agricultural monitoring application) that can then be related to the global coordinate system if so required. We also require techniques for generating the location information. While GPS[44] can be used for a number of applications, it is not adequate for all applications requiring location information. Location information may also be used directly by the network itself. For example, several applications (especially in sensor networks) have needs for location-based addressing. It is therefore important for the network to accommodate adequate representations of time and space to support real-time and embedded applications.

Currently, there are a number of localization technologies[45][46][47][48] that provide different accuracy resolutions and coverage ranges. The resolution may range from hundreds of feet (e.g. in flight tracking), to inches or less (e.g. as in-car and body-worn networks[49]). As we move towards the future real-time and embedded system networks, more ubiquitous localization techniques that provide fine-grained localization accuracy and are widely deployed, will be needed.

Similarly, as these networks develop, new protocols for clock synchronization that achieve fine-grained resolution and wide scalability will be needed. The synchronization protocols will have to cover different scales of deployment covering in-car and body-worn networks[50], local area networks[51], wireless sensor networks and wide area networks[52].

Regardless of the future localization technologies and time synchronization protocols that need to be developed, a globally consistent representation of time and physical location is a prerequisite for monitoring and coordinating responses in distributed real-time applications. While the spatial and temporal resolutions needed are technology dependent, the representation must be consistent. Furthermore, users must be informed about the resolutions available in each of their areas of interest. GENI offers the opportunity to experiment with protocol design for consistent representation of time and location with adequate precision and synchronization to support real-time applications.

[44] P. Enge and P. Misra. Special issue on GPS: The Global Positioning System. Proceedings of the IEEE, pages 3–172, January 1999.
[45] M. Youssef and A. Agrawala, "The Horus WLAN Location Determination System," In the Third International Conference on Mobile Systems, Applications, and Services (MobiSys 2005), June 2005.
[46] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The Cricket Location-Support System," In the 6th ACM MOBICOM, Boston, MA, August 2000.
[47] S. Tekinay, "Special issue on Wireless Geolocation Systems and Services," IEEE Communications Magazine, April 1998.
[48] R. Want, A. Hopper, V. Falco, and J. Gibbons, "The Active Badge Location System," ACM Transactions on Information Systems, 10(1):91–102, January 1992.
[49] A. Nandan, S. Das, G. Pau, M.Y. Sanadidi and M. Gerla, "Cooperative downloading in vehicular wireless ad-hoc networks", Proceedings of Wireless On-Demand Networks and Services, January 2005.
[50] A. Nandan, S. Das, G. Pau, M.Y. Sanadidi and M. Gerla, "Cooperative downloading in vehicular wireless ad-hoc networks", Proceedings of Wireless On-Demand Networks and Services, January 2005.
[51] http://ieee1588.nist.gov/
[52] D. L. Mills, "RFC 958 - Network Time Protocol (NTP)," September 1985.

4.2 Timing Predictability

Layering, multiplexing and virtualization in the current Internet introduce convenient abstractions but often obscure key underlying timing characteristics such as delay, jitter and sometimes packet loss. It is important to note that we need distributed timing predictability within a geographical area to support distributed real-time control, such as stabilizing an electrical transmission network when power generation equipment or transmission lines fail.

Timing and jitter are not only network technology and protocol dependent, but also workload dependent. Users need to know precise conditions under which various bounds hold, including wireless networks with dynamic topologies. Furthermore, admission and workload control must be a built-in part of the design. Note that communication without excessive delays is often required under stress conditions in which the workload becomes high, but for the control systems to function, communications (e.g., messages from sensors to controllers) must not only be delivered, but also arrive within the necessary time bounds. Supporting distributed “bounded delay zones” is a crucial challenge.

The current QoS solutions for the Internet (e.g. DiffServ[53] and IntServ[54]) and for wireless networks[55] need to be reconsidered. GENI will enable research on new or updated approaches that investigate radically new techniques to provide more predictable end-to-end performance guarantees over multiple administrative domains. The new network stack will assure the delivery of data within specifiable delay bounds, which may be tight and known and with very small delay jitter and known loss characteristics. In turn, such timing predictability will enable a number of new applications such as those described in the previous section.

4.3 Security, Anti-tampering and Survivability

Security is concerned with the capability to prevent information and system resources from being used or altered by unauthorized users. A thoughtful discussion on this subject can be found on the GENI website[56]. In addition to cyber attacks, there are unique challenges from the perspective of embedded systems. Unlike office computers, embedded monitoring devices are often left unattended for long periods of time in remote areas and may be subject to tampering. For example, compromised unattended physical sensors may feed the system with false data while the device remains authenticated and the transmitted data encrypted properly. It is also easy to manipulate the environment to fool many forms of sensors such as temperature, chemical concentration, electromagnetic and acoustic sensors.

Checks and balances must be built into the network at different layers of the architecture to detect and handle compromised devices. This includes correlating sensors’ inputs, model-based checking for data validity, and other anti-tampering technologies to prevent altering of devices. Physical security and integrity of devices may be assured by deploying imaging and motion

[53] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, W. Weiss, “An Architecture for Differentiated Services,” RFC 2475, IETF, December 1998.
[54] R. Braden, D. Clark, S. Shenker, “Integrated Services in the Internet Architecture: an Overview,” RFC 1633, IETF, June 1994.
[55] G. Pau, D. Maniezzo, S. Das, Y. Lim, J. Pyon, H. Yu, M. Gerla, “A cross-layer framework for wireless LAN QoS support”, Proceedings of IEEE ITRE, August, 2003.
[56] http://www.geni.net/references.php

detection devices to detect the presence of unauthorized persons. Techniques to limit the damage caused by compromised devices need to be developed. Verification of reported location information must be built into systems flexibly and rigorously, while protecting users' privacy. Although a number of location verification algorithms are available[57] [58], new research is still needed to make them more practical and scalable. These techniques also have implications for network protocol design, for example, to enable discarding of packets based on security considerations. Generally, at the network level, automatic detection and isolation of compromised parts of the system are needed, along with support for high degrees of security for unattended devices and location verification.

4.4 Reliability/Availability, Robustness and System Stability

Reliability and availability relate to the probability of working continuously for a given duration and the percentage of up-time, respectively. For safety critical real-time applications, reliability is a key concern. This means that the network needs to provide built-in support for redundancy management to guard against component and link failures. Robustness is the ability of the system to perform acceptably when the system operates outside of nominal conditions. For example, the ability to create disjoint routing paths may improve robustness by eliminating certain common failure modes. Stability is concerned with the system's ability to keep disruptions contained. Both of these quality attributes are critical to the success of networks that support real-time and embedded applications. How to specify, identify and validate these attributes will be an important research topic, particularly when disruptions are caused by software faults or malicious attacks. The rate of software faults has far exceeded the rate of hardware faults.

Cascading failures are the antithesis of reliability, availability, robustness and stability. There have been various cascading failures in both electric networks and telecommunication networks in the past. The effective prevention of failure cascades in the network infrastructure is a critical issue for real-time and embedded computing. One way of monitoring operations and detecting failures is through traffic sniffing, especially in the shared wireless medium. Techniques such as those in the framework for wireless LAN[59], can be used to non-intrusively monitor traffic and detect problems. At the network level, assured delivery of data with detectable failures, and a support for graceful degradation when failures or overload conditions arise is required. Beyond these approaches, however, new research is needed to determine how they can be integrated and complement other techniques to ensure effective failure cascade detection. Interdiction and mitigation can be achieved within the particular context of each of a wide range of distributed real-time and embedded systems.

4.5 Safety

[57] N. Sastry and U. Shankar and D. Wagner, "Secure Verification of Location Claims," Technical Report UCB//CSD-03-1245, EECS, UCB, 2003.
[58] D. Singelee and B. Preneel, "Location Verification Using Secure Distance Bounding Protocols," IEEE International Conference on Mobile Adhoc and Sensor Systems Conference, 2005.
[59] Jihwang Yeo, Moustafa Youssef, and Ashok Agrawala, "A Framework for Wireless LAN Monitoring and Its Applications," ACM Workshop on Wireless Security (WiSe 2004) in conjunction with ACM MobiCom 2004, Philadelphia, PA, US, October 2004.

Safety is concerned with the prevention of the loss of life and/or serious damage to people, property or the environment. Sharing of resources in the network compounds the challenges of safety. When we connect systems with different degrees of criticality together and let them share resources, the development of a certifiably safe infrastructure becomes a serious challenge. Many of the quality attributes mentioned above such as real-time, reliability, security and stability also impact safety. In addition to technology issues, certification (see Section 4.12) and liability management are other important challenges.

For example, many medical dispensing devices are safety critical. They are currently certified as stand-alone devices under a specific set of application contexts. If we connect several of them together and something goes wrong, how can we define and identify which device is responsible? In the new interconnected environment, how is safety specified? How do we certify it? These questions become impossible to answer unless the lower level supporting infrastructure is also certified. Currently, the commercial infrastructure assumes absolutely no liability for its impact on constraints at higher architectural levels. Furthermore, typically such systems have many known and unknown bugs. Changing the legal and liability system will be hard. GENI offers a unique opportunity to design certifiable protocols from the wire upwards creating entire stacks that are compliant with the certification requirements of critical applications. The slicing mechanism in GENI could further isolate such stacks from other non-certified protocols and applications. Technologies for isolation and protection across all the layers along with controlled graceful degradation of service can arise as an important research product enabled by GENI.

4.6 Privacy

The pervasiveness of real-time embedded systems of the future will bring tremendous advantages, including enhanced quality of life and advances in real-time remote medical care. Along with this pervasiveness comes the difficult issue of also providing privacy. New dynamic, cross system, real-time privacy mechanisms must be developed. Privacy policies are and will be increasingly specified at different levels of detail and have different semantics for different systems. Techniques for specifying and checking the consistency of policies across separate systems are needed. For example, privacy policies for hospitals, insurance companies and pharmacies must be coordinated and consistent to protect individuals' privacy according to their expressed preferences. These policies also must be dynamic, perhaps as a function of a person's health condition and medical directives. As queries for information are issued it is necessary to enforce the privacy policies in real-time. It is very important to consider the impact of privacy solutions on the real-time networking infrastructure, including addressing, routing, timestamping, encryption and avoidance of communication patterns that can reveal private information. GENI will catalyze research on innovative privacy-preserving protocol stacks that meet the requirements of privacy-sensitive embedded systems.

4.7 End-to-End Composition and QoS

Large scale real-time and embedded systems will often be constructed with well-defined components and sub-system composition relationships. Such components and associated composition methodologies must address more than functional concerns. There is a need to develop composition techniques that can provide end-to-end guarantees for multiple QoS properties such as meeting real-time requirements, safety, reliability, fault tolerance, security and privacy. The resultant system must also satisfy control and actuation requirements. Since real-time and embedded systems vary from highly safety critical to high performance systems, there is a need for new QoS specifications, runtime techniques to enforce these end-to-end specifications, and associated analysis and prediction techniques. Underlying networks must provide the basic capabilities to permit a wide range of composition solutions and QoS mechanisms to be developed and deployed. For example, event-based versus time triggered architectures are currently debated as alternative underlying structures for end-to-end composition. This presents tremendous challenges in wireless networking, as the wireless medium is essentially the *space* shared by users in the vicinity of each other, and QoS mechanisms must account for user end-to-end specifications, and dynamic environmental changes, such as path loss, multi-path fading, and interferences. New architectures based on event-/time-triggered schemes or hybrid schemes that combine elements of both approaches should be investigated atop GENI in support of real-time and embedded computing demands.

4.8 Interoperability with Wireless Networks and Sensor Networks

There have been great advances in wireless networking technologies in recent years. Communication networks must take into account the fact that many future systems will be highly interconnected. In fact, some systems will consist of sets of wireless sensor networks possibly interconnected via the Internet. Many of the wireless networks may use different protocol families. This heterogeneity raises many major research issues. First, a unified addressing mechanism that copes with mobility and scalability should be incorporated as part of the network protocol stack. Second, in spite of the fact that the communication media is now shared in the space (rather than a dedicated link) and subject to environmental dynamics, QoS in the temporal and spectral domains must be provisioned to ensure the timing properties required by applications such as distributed control and surveillance. Third, inherent wireless radio characteristics give rise to less reliable communication and topology dynamics that are not found in wired networks. Fourth, typical resource constrained devices require new lightweight security techniques, which must be addressed fundamentally as systems are being designed and not added as an afterthought.

There is also a set of research issues that must be considered to ensure seamless integration of the core Internet and wireless sensor networks. As location information becomes more pervasive in future wireless sensor applications, location information can be used for addressing, requiring protocols that correlate physical context routable address. Several new functionalities that were not supported in the current Internet have become essential in wireless sensor networks – lightweight localization, fine-granularity time synchronization, data aggregation and in-network processing. Current proposals for wireless network protocols should be reexamined in the light of the above challenges to allow use of wireless sensor networks to support timing and other requirements identified earlier.

4.9 Scalability

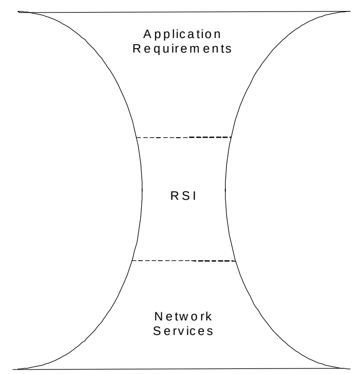
In the future, sensor and embedded devices will be used at ultra-large scales, including millions of devices connected over the Internet. For example, world-wide weather monitoring based on millions of new sensor devices is being contemplated. New network architecture must be designed to support such a large number of devices that interact across large geographic areas.

The architecture should scale to cover the expected large number of devices with a suitably minimal effect on performance.

With scalability, the issues of self-calibration, self-configuration and "self-healing" become crucial. Also, managing such a large-scale real-time network that spans multiple administrative domains becomes a major challenge. It is also important to understand how to create and control aggregate behavior in such large scale decentralized systems and develop network protocols and architectures that facilitate such decentralized operation and control. All challenges described in this section should be addressed from the beginning with scalability as a central principle; a challenge that lends itself well to investigation on the proposed large-scale GENI substrate.

4.10 Requirements-Services Interface (RSI)

A common characteristic of the types of applications envisioned is that they interact with physical systems that have their own dynamics. As a consequence, all such applications have well defined timing requirements for sensing and control loops across local as well as wide area deployments. Each loop can have different periods and sensitivities to delay and jitter as well as to message loss. In addition, safety critical applications demand a high degree of reliability in communication. Often they also require auditing trails for certification and administration procedures (e.g., to verify that the system can indeed tolerate the faults and failures specified by the stipulated fault model). Clearly, all components of such a safety critical system, including the portion of the network involved, must conform to the application-specified requirements. When running classified applications, there may also be data encryption requirements that must be supported by the system. Certification often requires traceability across all the critical components of the system, including the hardware and software, of the end system and network elements.



The communication capabilities of the system are provided by the underlying network infrastructure. Often the application designers and the network designers for a system are different groups of people. The requirements for communications are generated by the application designers while the service provisioning specification is generated by the network designers. To facilitate a wide range of research, the two communities have to maintain an effective communication using a Requirements Services Interface (RSI) so as to optimize the overall system. Such communication can be facilitated by the development of multiple standardized RSIs for various application domains. It is valuable to create several specific RSIs based on current systems. It is also important that these RSIs not constrain emerging and new research areas (a similar problem to the current constraining of capabilities by fixed attributes of the Internet). Slicing and virtualization in GENI are mechanisms that can support coexistence of multiple RSIs (in different slices of the network), while permitting other research that can utilize the "bare" system.

Note that RSIs not only have an important role at design time for co-optimization of the configuration of an application and the networking services, but can also be used at run time through automated negotiations and optimizations. The basic role of an RSI is to become the framework for interaction between the application and the network, as defined by the two communities. An RSI needs to:

- Identify the services provided by the network, along with the quality and pricing attributes of such services.
- Abstract the network properties to a standardized set of QoS service classes that can be realized economically by the underlying networking infrastructure.
- Quantify the diverse application level QoS requirements in such a way that the requirements can be met by selecting from the available QoS service classes.

From the perspective of networking research, RSI is a useful requirements engineering framework in which to consider the design of different layers of the protocol stack so as to enable more fine-grained and coordinated specifications of desired network capabilities.

4.11 Built-in Support at the Middleware Level

GENI is an infrastructure designed for the development and deployment of new protocols and services for systems of networked devices. A repository of middleware infrastructure will facilitate research on the testbed without requiring each research group to re-invent the infrastructure it needs. The management of quality attributes should be supported uniformly by the middleware to ensure consistency and reduce the burden of application development. Middleware for real-time and embedded computing needs to provide services including:

- Time and location services.
- Real-time and best-effort delivery of events.
- Primitives to support the formation of real-time collaborative groups with
  - Consistent views of distributed states in real-time, and consistent distributed real-time actions (resolution is technology dependent).
  - Topology control and packaged service classes with known QoS specifications under precisely specified conditions.
  - QoS controlled VPNs across wired and wireless, private and public networks.
- Interfaces: access to the same types of controls regardless of the underlying network technology.
- Support for isolation, protection and dependency tracking and management to ensure safety in using resources shared between safety-critical and non-safety-critical applications.
- Support for instrumentation for evidence based certification.
- Support for mobility.
- Support for security and privacy.
- Support for “self-healing” services.

4.12 Compatibility and Certification

With the growth of different applications and services in the future Internet, architectural mechanisms are needed to support different classes of services These include traditional best-effort data services and different classes of managed and guaranteed QoS services. More importantly, the design of some new protocol stacks may need to be compatible with regulatory organizations' certification and auditing requirements. For example, Application Domain I would require designs that facilitate FDA certification for components and systems including instrumentation, evidence collection, and innovative certification processes. This capability will also allow different administrative domains to use a common set of standard interfaces and terminologies, thus reducing the burden of administrative management and overhead.

5. Engineering Issues in the GENI Substrate

A number of key engineering issues also must be addressed in the GENI substrate to support real-time and embedded systems research. We note that the following discussion is from the perspective of the real-time and embedded systems community. Additional discussion with the GENI community is needed to further elaborate toward a complete understanding and possible modification of the key ideas related to these issues. Specific APIs must also be created that encapsulate the substrate capabilities detailed here.

Virtualization and Slice Semantics: Virtualization and slice semantics are central to the GENI substrate. Slicing is the fundamental mechanism needed to achieve isolation and to provide "sandboxes" for experimentation with innovative protocols and software technologies. Several requirements must be satisfied in the design of the mechanisms that support the slicing abstraction. At a high level, to support real-time and embedded applications, virtualization and slicing mechanisms at each node must export clear timing semantics that are conducive to real-time guarantees. It is also necessary to support end-to-end virtualization, which may require coordination among multiple single-node slice schedules. The main requirements are as follows:

- *Predictable latency* – Virtualization and slicing mechanisms typically provide bandwidth guarantees (averaged over an appropriate time window). In contrast, real-time applications also require specifications on latency that individual (top of the queue) bits will experience in physical resource access within a slice. Deterministic specified latency does not follow automatically from deterministic specified rates. For real-time operation, it is necessary to have a multiplexing mechanism that provides deterministic latency for slices at a fine granularity (for example, 1 microsecond slice every 10 microseconds). This capability cannot be hidden by the virtualization layers.

- *Inter-slice synchronization* – For the network, end-to-end constraints across nodes are needed to achieve coordinated scheduling of slices. For example, if time-multiplexing is used, depending on how time slots are scheduled on adjacent resources, a different end-to-end latency may be experienced (consider the analogy with synchronized versus unsynchronized traffic lights). Simply using rates will not necessarily provide the tight guarantees that often are required. Pipelining of slices or timing-based resource reservation schemes is needed to provide tight but reasonably efficient end-to-end timeliness support

- *Repeatability* – Repeatability for real-time and embedded systems must not be perturbed by the virtualization policies and mechanisms. In this regard, service-level agreements for real-time experiments, system testing, certification runs and other key activities, should be given by the network.

It must also be possible to have detailed specificity of time, location and resources, including potentially the entire (specific) end-to-end route. This is not always required, but the capability must exist to achieve a fine granularity of determinism from the perspective of research and development. The specification should also permit a notion of the degree or importance for meeting these requirements in terms of a quality of service attribute.

Time: We need a fine-grained uniform notion of time at the microsecond timescale (or smaller). Synchronized clocks at sub-microsecond granularity are required. The ability to timestamp an event accurately is required. For example, one solution might be for routers or network interface cards to have an interface to read time at the latest moment possible before transmitting a packet. This serves to reduce non-determinism between when an event actually occurs and when it is recorded.

Location: We need a uniform 3D representation of physical location.

Observability: Observability in real-time systems can intimately affect the application itself. Consequently, instrumentation must be predictable. This means that observability either needs to be unobtrusive (e.g., by utilizing parallel instruments that do not affect the timing) or the impact of the observations must be deterministic and its impact subsequently accounted for in the analysis of the system. Observability can be supported by mechanisms such as fine-grained real-time logging, dedicated data transmission paths, and other mechanisms. These mechanisms must not perturb the timing behavior of flows perhaps using dedicated hardware to support observability.

Certifiability: Many real-time and embedded systems are used in safety critical applications and they must be certified. It is necessary to have a substrate that can serve as a basis upon which to perform certification research. To do this, verifiability is required. In addition to the careful slice semantics discussed above, a good start for this work would be for every critical component to be measurable with respect to its reliability and users should be able to collect data about failures and failure modes. Slices should also provide isolation of failures and the efficacy of isolation mechanisms should be verifiable and testable for evidence collection. With these capabilities the GENI substrate should provide a path for performing highly beneficial certification research.

Technology and Hardware in GENI: In addition to the GENI backbone hardware, the anticipated technology and hardware to perform real-time and embedded systems research include:

- Four large wireless sensor networks of approximately 1000 nodes each.
- Sensor suites including various classes of sensors such as temperature, acoustic, biometric and video sensors, with upgrades and new sensor types added over time as required.
- Actuators should include low power actuators and some that require higher power (with associated motors and power sources); this is required to support end-to-end control research.

- Communication devices that support various bandwidths and ranges including multi-frequency devices and devices with directional antennas.
- Instrumentation that can overhear messages and support passive observability; other instrumentation for measuring power, collecting experimental data, etc.
- Devices should have sleep modes and other power savings modes.

End-to-end (across networks) testing should be possible, probably by a combination of co-sharing and reservations. These networks should be generic testbeds managed by GENI. Support for tests should include live “targets” (perhaps robots) as well as synthetic load generation.

6. Summary and Recommendation

One of the most pervasive, society-transforming changes brought about by advances in computer science has been the convergence of computing and networking that has given us the Internet. This merging of technologies has fundamentally changed how corporations, governments and individual citizens receive, manage and deliver information and services. The logical next step is to enable the convergence between computing, networking and intelligent sensing and control of the physical environment.

Unfortunately, there exists a mismatch between the design of the original "best-effort" Internet protocols and the requirements of many current and emerging applications, which combine demands for connectivity and bandwidth with needs for fine-grained timing guarantees. The mismatch between the current Internet architecture and fundamental requirements of real-time applications has forced industries concerned with real-time applications to create a number of *one-off* domain specific network protocols. The proliferation of such special-purpose de facto real-time networking standards increases cost and creates inter-operability problems when these different networks are linked together.

What we need is an integrated networking, middleware and application integration framework that will not only replace these one-off domain specific protocols but also will foster countless new technological innovations, products and services that will be qualitatively better than what the World Wide Web currently can offer. There are numerous examples of emerging applications that can be enabled by a time-sensitive network backbone. For instance, immersive tele-presence applications are now close to becoming a reality. It will soon be possible to stitch together virtual 3D environments where large numbers of participants can interact, exchange digital copies of various artifacts and generally maintain the perception of presence in a shared physical space. If perfected, such technology may significantly improve collaboration, outreach, education and business activities. It can also reduce the need for travel, while increasing productivity due to reduced commute times. However, realistic tele-presence requires very low latency communication and a high degree of synchronization among large data flows, potentially spread across a wide-area network, and unfortunately current Internet protocols do not meet such tight timing constraints.

Another category of applications that can be enabled by our proposed framework includes distributed control applications. For example, distributed prevention of cascading power blackouts requires tight real-time synchronization of multiple power stations across a wide area network in the presence of unpredictable events that may otherwise trigger a large-scale destructive chain reaction. The performance and stability of these applications is sensitive to loss, delay and jitter. Significant financial and societal disruptions can therefore be averted if the timing behavior of the Internet could be made as reliable as, say, certain security mechanisms such as encryption.

Furthermore, advances in sensors, wired and wireless networks and low-power intelligent devices are enabling an entirely new class of networked embedded applications in the sensing and monitoring of environmental conditions. A World-Wide Sensor Web is envisioned where myriads of sensors around the globe will feed real-time data into the Internet. In fact, it may well be that future growth in Internet traffic will be attributed primarily to embedded sources such as sensors, as opposed to human inputs which currently dominate.

The new framework can also enable fundamentally new approaches to privacy, security and mobility which are better integrated with core networking protocols. Investigation of such new approaches requires co-design of both core and edge network support, a feature uniquely afforded by the GENI facility.

There are many networking challenges in the creation of the scientific and technological foundations needed for convergence of real-time computing, communication, sensing and distributed control. To this end, a top-down approach is taken towards distilling the key requirements from many existing and next generation applications. Categorizing them into five main application domains which will have profound impacts to our society, are:

(1) medical and health management systems
(2) command, control and communications systems
(3) productivity enhancement and environmental protection
(4) electrical distribution networks and
(5) future applications such as tele-immersion.

The key common requirements of these applications include:

- Uniform representation of time and physical location information,
- End to end timing predictability across wired and wireless mobile networks,
- Co-existence of guaranteed, managed and best-effort QoS services,
- Quantified safety, reliability, availability, security and privacy,
- Scalability across small deployments to national and world-wide deployments, and
- Compatibility with regulatory organizations' requirements.

Overall recommendations of the RT and Embedded GENI workshops to NSF, the research community, and real-time user communities currently having their own standards, are summarized as follows:

For the NSF:

Recommendation 1: Create a New Research Program - Sponsor a research program for the creation, analysis, experimentation and validation of new distributed real-time and embedded capabilities and services. These services are aimed at seamlessly integrating the physical world and the cyber world, facilitating the development of applications that span these previously isolated boundaries. The research program should take a system view, addressing not only the networking but also all the upper layers including OS, middleware, distributed system architectures and high assurance computing technologies for real-time and embedded applications.

Recommendation 2: Collaborative Experimental Systems Research - Encourage collaborative research resulting in end-to-end deployment and evaluation of future real-time and embedded applications over the future Real-time and Embedded GENI.

Recommendation 3: Create a Facility – Create a facility that would allow experimentation on a large scale with real users and applications, and sponsor national level, open and shared experimental facilities and testbeds for the validation of new research results in real-time and embedded GENI. As there are several different aspects of real-time and embedded systems, this infrastructure should include:

- Integrated and configurable backbone and edge network infrastructure consisting of both wired and wireless networks;
- Facilities suitable for real-time and embedded application experiments, so that different communities including medical, avionics, automotive, process control, defense and security, emergency response, environmental monitoring, power generation and distribution, among others, can experiment with real-time and embedded GENI technologies.

Recommendation 4: Create an Advisory Board - Create an advisory board that includes representatives of the networking, real-time, embedded, and application communities. This board will be charged with developing the requirements and services interface specifications (RSIs) that articulate the specific interfaces needed for real-time applications. The board will also oversee the design of the GENI facility making sure that it is compliant with such specifications. The specifications will primarily address two domains:

- Specifications are needed for the timing semantics of the basic slicing mechanisms. These mechanisms must ensure that slices can provide crisp bandwidth and latency guarantees that are not obfuscated by layers of virtualization and multiplexing.
- Specifications are needed on the representation and synchronization accuracy of global time. Sub-millisecond accuracy may be needed for some applications.

The advisory broad should oversee the creation of working groups, such as middleware, certification, RSI, security, etc., for the support of various aspects of the facilities and testbeds.

For research community:

Recommendation 5: Focus on the research problems and create networking and middleware primitives – Focus on identifying and working on the key research problems in the area and create networking level primitives and middleware, compliant with the RSI and the recommendations of the advisory board that can:

- Provide uniform representation of time and physical location across all networking media.
- Provide predictable and bounded delay and jitters for communications with specified conditions under which such bounds hold.

- Support auditing and evidence based certification for safety critical and high consequence applications.
- Support the evolution of underlying technologies and application requirements;.
- Support automatic fault injection tests, fault identification and isolation mechanisms.
- Support automatic tracing, diagnosing and reporting of operating conditions and anomalies.
- Support key common requirements identified in this report, in addition to the standard middleware services such as naming.
- Embody a set of highly reusable protocol modules that can be customized for different application domains. These protocols must be designed, prototyped and evaluated to reduce the development cost for specific application domains. They must enable interoperability between diverse real-time and embedded applications and address energy, mobility, and end-host device limitations. Such protocols must handle highly diverse QoS requirements including delay bounds, data rates, geographical distributions, scales and flow characteristics, in addition to safety, security and reliability requirements.

Recommendation 6: Focus on experimental systems research and create a global repository of research artifacts – While focusing on experimental systems research, create a variety of research artifacts which are kept in a global repository. This repository will improve reuse of research results, allow for better integration, contribute to improved understanding of the state of the art, supply documentation and generally allow the community to focus their effort around a growing set of tools and protocols developed for representative application categories.

Recommendation 7: Focus on refining RSI - Create a Requirements and Services Interface (RSI) that would support networking, computing, real-time, embedded and application communities to collaborate synergistically.

For the user community with their own networking standards:

Recommendation 8: Active Participation - Continue in the participation and collaboration of RT and Embedded GENI efforts and

- Articulate the unique challenges and requirements in specific application areas.
- Help to develop RSI and other areas to ensure that domain specific needs are met.
- Assist in the experimental evaluation of the new technologies for their domains to ensure that the common technology can replace one of a kind standard.

Appendix A. System Of Networked Embedded Devices Planning Session

College Park, MD
October 7, 2005

Attendees

Ashok Agrawala, University of Maryland
Lui Sha, University of Illinois
Tarek Abdelzaher, University of Illinois
Kirstie Bellman, Aerospace Corporation
Bobby Bhattachajee, University of Maryland
Tom Conte, North Carolina State University
Helen Gill, National Science Foundation
J. Gowens, Computational & Info Sciences Directorate
Roch Guerin, University of Pennsylvania
Haiyun Luo, University of Illinois
Howard Marsh, OSD-ATL
Guru Parulkar, National Science Foundation
Raj Rajkumar, Carnegie Mellon University
Kang Shin, University of Michigan
Sang Son, University of Virginia
Neil Spring, University of Maryland
Jon Turner, Washington University at St. Louis
Wei Zhao, National Science Foundation
Christian Halaschek-Wiener, University of Maryland
Morgan Kleene, Univeristy of Maryland
Moustafa Youssef, University of Maryland

Appendix B. The RealTime GENI Workshop - Reston, Virginia

February 6 and 7, 2006
Attendees List

Tarek Abdelzaher, University of Illinois – UC
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Matthew Andrews, Bell Labs
Panos Antsaklis, University of Notre Dame
Azer Bestavros, Boston University
Bobby Bhattacharjee, University of Maryland
Michael Branicky, Case Western Reserve
Dave Clark, Massachusetts Inst. of Technology
Reggie Cole, Lockhead Martin
John Eidson, Agilent
Darleen Fisher, National Science Foundation
Chris Gill, Washington University at St. Louis
Helen Gill, National Science Foundation
Julian Goldman, Massachusetts General Hospital
Rajesh Gupta, University of California, San Diego
Sally Howe, National Coord Office
Raj Jain, Washington University at St. Louis
Kevin Jeffay, University of North Carolina
Frankie King, National Coord Office
Herman Kopetz, TU Wien, TTTech
Teja Kuriganti, Extreme Measurement Comm Center
Jim Kurose, University of Massachusetts
TV Lakshman, Bell Labs
Karl Levitt, National Science Foundation
Joe Loyall, BBN
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Kenneth Marko, ETAS
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Al Mok, University of Texas
Daniel Mosse, University of Pittsburg
George Pappas, University of Pennsylvania
Guru Parulkar, National Science Foundation
Raj Rajkumar, Carnegie Mellon University
John Rushby, SRI

Henning Schulzrinne, Columbia University
Lui Sha, University of Illinois – UC
Kang Shin, University of Michigan
Jack Stankovic, University of Virginia
Janos Sztipanovits, Vanderbilt University
Paulo Tabuada, University of Notre Dame
Kristen Tsapis, University of Pittsburgh
Karsten Wehefritz, FlexRay Consortium
Sandy Weininger, Food and Drug Administration
John Wroclaski, ISI
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Taieb Znati, University of Pittsburgh