Innovation in Networking

Nick McKeown
Stanford University

Guru Parulkar
Stanford University

Jennifer Rexford
Princeton University

Version 10: December 14, 2008[1]

The Internet has become an enormously powerful engine for innovation. Originally a sandbox for researchers, it has enabled the creation of revolutionary products and services that have stimulated economic growth and transformed the everyday lives of billions of people around the globe. Its impact can be observed in sectors as diverse as education, healthcare, entertainment, commerce, finance, and civil infrastructure.

Ironically, although the US has always enjoyed a world leadership position in state-of-the-art networking architectures, technologies and applications, we have failed to capitalize on the full economic and social potential of broadband networks. In 2008, China surpassed the US as the nation with the largest number of Internet users, and in broadband deployment the US ranked only 15th of 30 OECD countries. To remedy this, the Administration is planning an economic stimulus investment that will provide last-mile, universal broadband capabilities.

In this essay, we seek to inform and leverage the Administration's plans by creating Broadband Innovation Incubators on the campuses of US colleges and universities, reinvigorating the wildly successful government-industry-university partnership that gave birth to and nurtured the growth and evolution of the current Internet.

A cumulative investment of $650 million is proposed[2], divided into two parts:

- A one-time stimulus investment of $300 million for subsidies[3] to 400 of the nation's colleges and universities to upgrade and "research-enable" on-campus wired and wireless broadband networks that reach every lab, classroom and dorm. (We assume that the more general broadband stimulus will provide enhanced connectivity to the edge of the campus.)

- An additional $70 million/year (5-year cost of $350 million) to support broadband and broadband-enabled research and education that will stimulate innovation and economic growth for many years to come.

A Campus-wide Broadband Strategy

We propose to reinvigorate the wildly successful government-industry-university partnership that gave birth to and nurtured the growth and evolution of the current Internet. Our goal is to leverage the Administration's plans to provide universal, last-mile broadband access to homes and organizations, including college campuses, by:

[1] For the most current version of this essay, as well as related essays, visit http://www.cra.org/ccc/initiatives
[2] These initiatives are included among those proposed in the essay "Infrastructure for eScience and eLearning in Higher Education: http://www.cra.org/ccc/docs/init/Infrastructure.pdf
[3] We estimate that the total cost to upgrade and "research enable" on-campus broadband networks at 400 colleges and universities is $600 million.

1. *Supporting the deployment of state-of-the-art, "research-enabled" wired and wireless broadband infrastructure on the campuses of 400 of the nation's colleges and universities to deliver broadband capabilities and services to every lab, classroom and dorm.*

   Colleges and universities will partner with organizations in industry and state and local government to earn federal subsidies totaling $300 million to upgrade on-campus broadband networks with both WiFi and fiber-based technologies, and to "research-enable" campus networks through the deployment of programmable routers and switches. (We assume that the more general broadband stimulus will provide enhanced connectivity to the edge of the campus.)

   By "research-enabled," we mean both the ability to conduct research on innovative networking technologies and applications, and the ability to be "early-adopters" of these innovations. To date, key network functionality has been placed in programmable computers at the network edge. This has enabled innovation in network services like the Web, peer-to-peer file sharing, and Internet telephony. Yet the inside of the network – which determines fundamental properties such as reliability, security and performance – has remained remarkably resistant to change, culminating in the emergence of contemporary network vulnerabilities with which we are all familiar. Embedding greater programmability into campus networks, as part of a general upgrade of bandwidth and reach, will enable research to improve network security, reliability, robustness and performance. It will also, we believe, unleash a new wave of innovations in broadband products and services. (The marginal cost of the research enablement – the programmability – is a small proportion of the total upgrade cost.)

2. *Supporting research and education activities that will assure US leadership in the development of new broadband products, applications and services for many years to come.*

   Colleges and universities will compete for National Science Foundation Broadband Innovation Incubator grants that support broadband and broadband-enabled research, education, and innovation. With an investment of $70 million/year (five-year cost of $350 million), Broadband Innovation Incubators will:

   - Stimulate both long- and short-term network science and engineering research engaging computer scientists, engineers, mathematicians, social scientists, and others;
   - Serve as testbeds for companies to experiment with new broadband products and services;
   - Support exploration of a wide range of eScience, eHealth and eGovernment applications;
   - Promote campus or regional competitions on the development for compelling broadband applications and applications software;
   - Provide platforms for exploring new educational paradigms; and
   - Provide vehicles by which to understand the societal changes prompted by emerging social network paradigms.

   Researchers will address a number of research challenges critical to the creation of a safer,

self-sustaining Internet that is more secure, more reliable, supports seamless mobility, and provides higher levels of performance. Research challenges to be explored include, but are not limited to:

- *Securing the Internet:* Current Internet-enabled innovations have revealed a plethora of security problems, including identity theft, spam and denial-of-service attacks. Compromised end-host devices can wreak substantial damage on Web servers, end users, and the network itself. While reducing software vulnerabilities and improving security practices can help, researchers must explore new networking architectures, technologies and other approaches to minimize the collateral damage caused by compromised end-host devices.
- *Assuring Seamless Mobility:* With the proliferation of cell phones, PDAs, and laptop computers, end-host devices are increasingly mobile, and users increasingly demand seamless communication on the move. In addition, virtual servers in data centers often move from one physical computer to another to balance load and reduce energy consumption. Research must be done to identify the network architectures, technologies and approaches necessary to support seamless host mobility.
- *Improving Internet Reliability:* The Internet is remarkably vulnerable to equipment failures, as evidenced by serious disruptions in communications during the recent Taiwan earthquake and a fiber cut in the Mediterranean Sea. Routers are slow to compute new paths to circumvent failures and sometimes paths are never found, despite the availability of alternative fiber paths. In addition, hidden dependencies – such as the multiple fiber optic cables affected by the Baltimore tunnel fire a few years ago – often compromise network reliability.
- *Providing Robust Network Management:* More than half the cost of a network consists of the people and systems that manage the equipment; yet more than half of network outages are caused by operator error. Future networks must be designed to adapt automatically to changing conditions based on higher-level policies specified by operators, to achieve greater reliability, performance and security at lower cost.
- *Exploring New Network Architectures:* The network of the future must be designed to accommodate the integration of unforeseen devices and communication media as well as yet unanticipated communication patterns. Thus, research on new network architectures/designs, including approaches flexible enough to accommodate several architectural implementations simultaneously, is essential.

Researchers will study and explore these and other research challenges, as well as innovative new products, services, physical devices and communication media, by building prototype systems and subjecting them to real user traffic and network conditions. *They will be able to evaluate new ideas not only via analysis, simulation and small-scale prototyping, but also through large-scale experimentation and deployment studies.*

These two parallel investments will harness the creativity and ingenuity resident in the nation's colleges and universities, allowing students and faculty to "live in the future" with ultra-high speed connectivity to state-of-the-art research and education resources and emerging broadband services.

A Unique Role for NSF and the NSF Community

NSF and the networking and distributed systems research community are uniquely qualified to participate in this activity. The NSF community is already engaged in a number of powerful, future-looking advanced networking research and research infrastructure projects that will inform broadband deployment and its transformative use.

For example, researchers in NSF-supported projects are currently taking a clean-slate approach to identify desirable future network architectures. In pursuit of a goal to provide 100 Mbit/s to 100 million homes, researchers in the 100 x 100 project are developing blueprints that re-prioritize the fundamental principles that underlie network design, to craft future networks that will be ubiquitous in scale, safe and secure, economically self-sustaining, resistant to attack, and tractable to manage. Further, a university-industry-not-for-profit alliance supported by NSF and led by BBN Technologies, is creating the world's first laboratory for large-scale experimentation with networks of the future and their evolving interactions with and impact on society.

NSF researchers in projects like the 100 x 100 project, as well as BBN and its alliance partners, are well positioned to inform the design, architecting and deployment of a broadband networks that will support large-scale networking research and applications innovations in addition to daily operations.

We believe that the Administration's investment in universal broadband, coupled with the investments described here, will assure our nation's future as ***the*** *world leader in broadband technologies and services.*

Deleted text

The National Science Foundation (NSF) has played a significant and enduring role in advanced networking. Together with the Defense Advanced Research Project Agency and other partners in industry and academe, NSF made some of the earliest investments in the Internet. The agency supported NSFNet, the first general-purpose research network, and oversaw its evolution into the global high-speed network of networks the Internet is today. NSF has continued to support a vibrant, academic networking and distributed systems research community that today assures US world leadership in networking architectures, technologies, and applications.

***For citation use*:** McKeown N., Parulkar G., & Rexford J. (2008). *Innovation in Networking*: A white paper prepared for the Computing Community Consortium committee of the Computing Research Association. http://cra.org/ccc/resources/ccc-led-whitepapers/