FCC Form 442 – Exhibit 6

Description of Research Project

Carnegie Mellon University

Next-Generation Mobile Network Testbed
CIT Infrastructure Investment Proposal

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Executive Summary
Mobile systems are rapidly overtaking their desk-bound counterparts as the dominant form of computation, yet the networks on which they are built bear the legacy thinking of pre-mobile systems. We propose the creation of a Next-Generation Mobile Network (NGMN) Testbed on the CMU-SV campus to re-think, from scratch, the way that networks supporting mobile computation should be built and to offer the opportunity for multiple faculty members and researchers to conduct experiments on a live mobile network. NGMNs start from the basic assumption that connections are unreliable and dynamic, in contrast to the legacy assumption from fixed networks that connections (fiber, copper) are reliable and static. We propose that any NGMN must be built from the assumption that mobile devices, network elements, and cloud-side applications must **share previously hidden state information** and **cooperate to optimize both network behavior and user experience**. Our proposed testbed exposes this information and creates the environment for a rich set of experiments, with the opportunity to evaluate user experience in real time.

Research Problem
While mobile computing has rapidly reshaped the way we live our lives, offering the promise of always-connectedness, the reality is less than one might expect. Radio shadow, variable channel characteristics, network congestion and other facts of wireless links have a negative impact on the user's experience. Long latencies deny desktop-like experiences, and the likelihood that these problems will simply go away with LTE-class networks is possibly more hope than reality. In addition, our ability to understand the behavior of the network at the system level is limited. Creation and validation of network models that incorporate these characteristics (and their impact on end-user experience) would lead to better network design, improved service quality, and the emergence of wholly new mobile opportunities that are impossible today.

We believe the problems stem from fundamental flaws in the architecture of the overall mobile system.

1. **Managing the inherently variable nature of the wireless connection** necessitates sharing knowledge about the wireless connection with its users – the mobile devices and the apps running on them as well as the cloud services to which they are tied. Yet, mobile networks mask this information from apps. In an attempt to cleanly separate network functionality into layers, we in fact have created this problem.
2. **Managing the use of precious energy** in mobile devices necessitates sharing knowledge about the device's (or the app's) intent with the network. Having the network provide app-specific support that offloads computation to, say, a nearby cell site would help to reduce on-device power. Letting apps and the network arrive at a mutually agreeable coding scheme for streaming media would also help. Yet, apps and their runtime systems have no way to share this information with the network.
3. **Managing optimal pricing of resources** in mobile systems necessitates real-time auctioning of scarce resources (computational power and network bandwidth) between consumers, *e.g.,* apps, and suppliers, *e.g.,* the network. Yet, network-pricing schemes are essentially static without the opportunity for differentiation based on quality of service – even though it is highly desired.

Commercial networks are not a suitable testbed for studying and creating solutions to these problems by their very nature (they are closed). And small in-lab networks are also unsuitable because the interesting research questions can only be addressed with real users and real traffic.

Strategic Need and Future Opportunity
A better approach is to design a network testbed from the ground up with the properties of (a) open interfaces that expose network meta-data to network clients, (b) open interfaces in apps that expose client meta-data to the network, (c) the means to embed computation directly in the network using application-level virtualization techniques (an extension of the "cloudlets" concept), (d) the means to aggregate and analyze network meta-data, client meta-data, and virtualization meta-data in real time, and (e) a real-time quality-of-service mechanism that allocates resources using an open market model.

Our current research in analytical processing (statistics, machine learning, and other analytical techniques) and in mobile user behavioral modeling applies directly to and benefits from open network architecture. Such a testbed will further enable our research in machine learning, visualization, and empirical validation of theoretical models. One example of this

is our work on visual analytics – the development of novel mathematical, computational, and visualization methods in which analytical processing and visualization facilitate interaction with and feedback from end-users, creating a kind of closed cyber-physical analytical loop. It is our hope that, even though the testbed will be built at modest scale, that our results in visualizing network and user dynamics will scale to much larger networks. Another example is empirical validation (or lack thereof) for theoretical models – critical to the usefulness of these models in actual network optimization. The present lack of "real-world" data available to academia has hampered such modeling and validation. Our hope is that an at-scale, realistic network could lead to a breakthrough in the creation of rich, validated models.

We propose the creation of such a network testbed using open software-defined radio base stations, software-defined networking, and mechanisms to support (a)-(e) above. This network will be operated on the SV campus initially with the desire to extend it to the Pittsburgh campus and possibly to the sites of other research partners. Students and faculty can opt-in to use the network and its advanced services. Researchers will have the freedom to create intelligent networking and app-optimization systems and study the benefits delivered to the users. Real-time analytics of the network and its behavior will help us refine and develop a formal model of optimal mobile network architecture.

The NGMN has the opportunity to become the focal point for substantial collaboration as indicated by the number of CMU-SV faculty who have elected to participate in this proposal. Further, the NGMN and its projects have the potential to be the basis for major center-level funding related to the future of mobile and embedded systems.

Note: operation of radio equipment in the cellular bands in the USA requires an experimental license from the FCC. There are precedents, and we anticipate being able to secure a license in a timely way.

Proposed Equipment, Infrastructure and Cost incl. tax

To build the NGMN Testbed on the CMU-SV campus, the following items are needed (total: $267K)

- LabView and Wireless Test license and 1 year of maintenance ($15K) – quote attached
- National Instruments PXI instrumented base station ($71K) – quote attached, see Important Note below
    - Controller ($6K)
    - Modules ($52K)
    - Chassis, cables, support ($14K)
- Computer display for PXI Base Station ($300)
- Software-defined base stations (4 @ $33K)
    - NI Universal Software Radio Peripheral N210 (4 @ $3K) – quote attached
    - Baseband processor (4 @ $3K) – commodity server available from many vendors
    - Clustered application processors (16 @ $5K) – commodity server available from many vendors
    - Software-defined networking processor (4 @ $3K) – commodity server available from many vendors
    - Computer Monitor (4 @ $300) – quote attached
    - Antennas, cabling, mounting, weatherproof enclosures, KVM switch (4 @ $3K)
- Phones (30 @ $500) – commodity, available from many vendors
- Second-level software-defined networking processor ($5K) – commodity server available from many vendors
- Server for data collection and mining, with monitor ($21K) – quote attached
- Miscellaneous ($5K)

IMPORTANT NOTE: Because this proposal includes a single PXI, it qualifies for NI's 10% Educational Discount rate. Our Educational proposal for Connected Embedded qualifies for their 25% discount because it is based on five PXI systems. NI has indicated that NGMN's PXI can qualify for a higher discount if both NGMN and Connected Embedded proposals are funded.

Number of Students Benefiting

Currently there are 180 students enrolled at CMU-SV, of which 39 are ECE PhD students. When operational, we expect the majority of students to opt-in, to benefit from, and to contribute experiential data to the testbed via their mobile phones. Given the current alignment of research programs at CMU-SV, we further anticipate that eventually half of the PhD students will be using the testbed for experimentation and research. Pittsburgh-based graduate students would be welcome to use the testbed as well, and we welcome the opportunity to extend the network to the Pittsburgh campus.

Department Head Support

Martin Griss, SV Director _____