Research Statement

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Unlike the wired core of the Internet, edge networks like mobile, sensor, and disruption-tolerant networks suffer from topological uncertainty, and disconnections due to myriad of factors including limited battery capacity on client devices, radio characteristics, and mobility. Hence, providing reliable, ubiquitous connectivity and always-on consistency for network applications in such mobile and sensor systems is non-trivial and challenging. However, the problem is of paramount importance given the proliferation of mobile and sensor devices like cellular phones, laptops, PDAs, and music players. My research addresses this problem through the design and implementation of robust, reliable, and highly optimized mobile and sensor systems capable of providing improved connectivity and always-on operation in a diverse range of pervasive scenarios.

Research goals: The goal of my research is the design, implementation, deployment, and analysis of systems capable of providing improved connectivity and always-on consistency in a diverse range of mobile and sensor environments. Additionally, my research also explores usability issues in mobile systems, location dependent mobile social systems, and understanding social and communication networks using graph and wavelet theory.

Research methods: My research is a symbiotic mix of system building and theoretical analysis. While building a real system helps me understand the practical issues involved, theoretical analysis goes beyond a specific system and helps extract principles that have broader scope and applicability. Another important feature of my research is the cross-disciplinary nature of my projects. I have used tools from physics (multiresolution analysis in topology construction) and control theory (energy management algorithms for relays in mobile networks) to design better systems.

Enhanced Connectivity and Consistency in Mobile Systems

The primary focus of my dissertation is to provide improved connectivity and always-on operation in mobile and sensor systems. The problem is challenging because of the following two factors. For a client device like a laptop or mobile phone, providing always-on communication is difficult due to limited battery capacity. For example, with the wireless radio on, the maximum battery lifetime of a laptop is a few hours. This begs the following question: *Is it possible to provide always-on operation at minimal energy consumption for mobile and sensor devices?* However, an always-on mobile client is not useful without always available connectivity. A primary obstacle to such ubiquitous connectivity is the quality of present infrastructure support for mobile clients. For example, consider popular organic Wi-Fi deployments. Most regions have little or no Wi-Fi coverage. Even in areas where access point density is high, coverage holes are common due to issues such as interference, congestion, and association problems. This observation leads to a second question: *Can inexpensive enhancements to already-existing unreliable networks make them reliable?* My dissertation research provides the basis to answer these two questions through client and infrastructure end modifications.

Client-end modifications

Mobile devices such as laptops do not have adequate battery capacity for constant processing and communication. Even by powering off unnecessary components, such as the screen and disk, current laptops only have a lifetime of a few hours. However, while PDAs and sensors are similarly limited in lifetime, a PDA's power requirement is an order-of-magnitude smaller than a laptop's, and a sensor's is an order-of-magnitude smaller than a PDA's. We argue that by combining these diverse platforms into a single integrated laptop, we can reduce the power cost of always-on operation. We have designed, implemented, and evaluated Turducken [MOBISYS 05], a

Hierarchical Power Management(HPM) architecture for building such an integrated mobile client. We focused on a particular instantiation of HPM, which provides high levels of consistency in a laptop by integrating two additional low power processors. Our evaluation demonstrates that a Turducken system has a lifetime of *ten times* that of a standard laptop while providing always-on operation.

While the Turducken implementation was specific to laptops, the HPM architecture can be applied to other mobile and sensor clients. For example, we used HPM to design Triage [MOBISYS 07], a tiered hardware and software architecture for sensor network microservers. Triage extends the lifetime of a microserver by combining two independent, but connected platforms: a high-power platform that provides the capability to execute complex tasks and a low-power platform that provides high responsiveness at low energy cost. The low-power platform acts similar to a medical triage unit, examining requests to find critical ones, and scheduling tasks to optimize the use of the high-power platform. The scheduling decision is based on evaluating each task's resource requirements using hardware-assisted profiling of execution time and energy usage. Using three microserver services, storage, network forwarding, and query processing, our evaluation shows that Triage provides a 300% increase in microserver lifetime over existing systems while providing probabilistic quality of service guarantees.

Infrastructure enhancements

While clients like Turducken and Triage can provide always-on operation, without proper infrastructure support (e.g., Wi-Fi or cellular access), the goal of ubiquitous connectivity will remain a myth. Unfortunately, organic Wi-Fi deployments and cellular networks (like 3G, GPRS) fail to provide 100% reliable connectivity—there are regions in a mobile network which lack cellular and Wi-Fi coverage.

One solution to improving coverage is to deploy supporting infrastructure including additional base stations, meshes, and relay nodes in mobile networks. However, each enhancement has different cost-performance trade-offs. To understand the trade-offs involved, we performed a comparison study of the three enhancements using a large scale deployment and a demonstrably accurate ODE-based analytical model [MOBICOM 08]. Based on our deployment and analysis we found that in several cases relays and mesh nodes can be a more cost-effective enhancement than base stations.

Encouraged by the enhancement estimates that relays and meshes can provide, we designed and deployed throwboxes [INFOCOM 07], an architecture for nodes capable of relaying traffic between mobile nodes. The system uses a multi-tiered, multi-radio, scalable, solar powered hardware platform. It employs an approximate heuristic for solving the NP-Hard problem of meeting an average power constraint while maximizing packets forwarded by it. We built and deployed prototype throwboxes in DOME—a bus-based mobile testbed and showed that a single throwbox with medium sized solar panels can last perpetually while improving packet delivery by 37% and reducing message delivery delay by at least 10%.

As ongoing research, we are exploring the feasibility of enhancing Wi-Fi based organic networks with a solar powered 900MHz mesh[1]. This idea is a generalization of the throwbox approach where relay nodes form a mesh over a 900MHz channel. The goal is to use the additional 900MHz channel to patch coverage holes in organic Wi-Fi deployments. We are currently designing algorithms for striping TCP flows across the 2.4GHz and 900MHz channels for improved connectivity at mobile clients. Since the mesh nodes (implemented using mote-class solar powered devices) are energy-constrained, the optimization problem involves splitting flows such that the lifetime of the throwbox nodes are maximized and most flows are active in spite of disruptions in the Wi-Fi network.

Other Network and Systems Research

In addition to my dissertation research, I have interest in diverse areas such as mobile social applications, mobile system usability, mobile testbed construction, and graph topology construction. I summarize some related projects I have worked on during by graduate studies.

As a Microsoft Research intern, we built Virtual Compass[2], a peer-based relative positioning system that detects nearby mobile devices and places them in a two-dimensional plane. Virtual Compass uses multiple radios (Wi-Fi and Bluetooth) and multihop relaying simultaneously to reduce distance estimation error and

[1]Paper in submission (with Hamed Soroush, Mark Corner, Brian Levine)

[2]Paper in submission (with Sharad Agarwal, Ranveer Chandra, Paramvir Bahl, Alec Wolman, Mark Corner)

increase device coverage. We use adaptive scanning and out-of-band coordination to explore trade-offs between energy consumption and the latency in detecting movement.

My research also explores the area of battery usability—understanding how users interact with batteries [UBICOMP 2007]. Through a systematic user study on battery use and recharge behavior (on laptops and cellular phones), we found that considerable amount of recharges were driven by location and time and those driven by battery levels occurred when battery level was high. Based on these observations, we designed, deployed, and evaluated a user- and statistics-driven energy management system, Llama, to exploit the battery energy in a user-adaptive and user-friendly fashion to better serve the user.

I am also interested in the design of testbeds for mobile experimentation, similar to the GENI initiative. I have been involved in the design, and implementation of a testbed for large-scale mobile experimentation called the Diverse Outdoor Mobile Environment(DOME)[3]. DOME consists of 40 computer-equipped buses, numerous battery-powered nomadic nodes, hundreds of organic Wi-Fi access points, and a 26-node municipal Wi-Fi mesh network. Our testbed is unique as it provides temporal, technological, and spatial diversity and can enable a broad range of experiments. Through the experience gained from the deployment, we have crystallized a set of design principles that others should use when constructing testbeds of their own, including those related to deploying and managing a diverse testbed, distributing experiments remotely, and fostering collaborations among testbed stakeholders.

In addition to systems research, I am also studying fundamental connectivity properties of networks[4]. As part of an internship at Intel Research, I worked on applying principles of diffusion wavelets to construct compressed graph topologies. We formulate multi-scale representations of properties such as degree distribution, degree correlation, and edge correlation, and demonstrate that many practical metrics on graphs can be captured through random graphs generated from highly compressed representations of these properties.

Future research

I would like to continue applying my analytical and systems building expertise to research problems related to *networks* in general and *mobile and sensors systems* in particular.

With the increasing popularity of smart-phones like the Apple iPhone, Nokia N95, Google GPhone, and Windows Mobile devices, simultaneously using diverse radio interfaces like 3G, Wi-Fi, and GPRS is going to be a primary challenge. I believe that my graduate research on mesh enhanced mobile networks can be directly applied to provide reliable connectivity for mobile phones using multiple radio interfaces. For example, coverage holes in 3G networks can be patched using organic Wi-Fi. However, since data connection on cellular phones is expensive compared to organic Wi-Fi, the criterion for splitting flows should be cost as well as energy and connection quality. I also want to explore the idea of splitting flows at the transport layer in mobile systems using application layer hints. For example, in an email application which can support delays of minutes, such a hint can help decide which radio is most appropriate to use.

In addition to mobile systems research, I plan to explore more fundamental areas of networking—for example, trying to understand the social interactions in mobile social networks using classical graph theory. I want to apply my knowledge on graph topology characterization to temporal graphs to try and understand which connectivity properties most influence the structure of dynamic graphs. Additionally, I plan to continue research on mobile social applications. As an extension to the Virtual Compass system, I want to explore the idea of annotating social graphs with user-activity information. Such an annotation provides a more complete social context. For example, in a conference setting, an individual not only wants to interact with friends around but with friends who are "not busy". I plan to use automatic sensor-based activity inferencing on mobile phones combined with peer-based localization to derive activity annotated social maps.

[3]Paper with Hamed Soroush, Mark Corner, Brian Levine, Brian Lynn

[4]Paper in preparation (with Kevin Fall, Mark Corner, David Jensen)