

Research Statement

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My research interests lie in the area of *networked computer systems*. I plan to advance the state-of-the-art of networked computing through the contribution of original ideas followed by translation of these ideas to end applications and products. I have decided to start my career in the industry to realize this career objective.

Wireless networks are on the verge of massive proliferation. The emergence of protocols like ZigBee, UWB, WiFi and WiMax have led to significant growth and innovation in the *multi-hop* sensor and mesh networks. *Sensor networks* enable pro-active computing by sensing the parameters of the physical world. There exists wide scope for enhancement of productivity and efficiency in such a networked environment. Tuning the network for the characteristics of specific application requirements widens this scope further. *Mesh networks* have the potential to provide ubiquitous connectivity and wireless peer-to-peer networking. One of the most challenging tasks is to realize this potential in a cost effective manner. In my future research, I want to develop networking protocols in these domains. My background and expertise in wireless, ad hoc, and sensor networks, summarized next, will enable me to help drive the wireless revolution. I have also enjoyed working in inter-disciplinary teams at Rice as part of several NSF funded projects.

Design of an adaptive sensor network architecture for multi-scale communication and collaboration is the focus of my PhD thesis, as part of the COMPASS project. I have designed adaptive protocols for routing, medium access scheduling and synchronization for the proposed architecture. As a leading member of the team, I have also worked in the project named PRAN — a system for enabling physical implementations of simulation models. This was an unique experience that reinforced in me the confidence of building real life systems. My research experience on scalable ad hoc networking systems and on network edge architectures have provided me with a broad background in the design of wired and wireless systems.

Sensor Network Architecture

Sensor networks have emerged as a promising tool for monitoring and actuating the physical world. It employs self-organizing networks of battery-powered wireless sensors that can sense, process and communicate. In sensor networks, energy is a critical resource, while intended applications exhibit a few specific characteristics. Consequently, there is both a need and an opportunity to optimize the network architecture for the specific applications in order to minimize resource utilization. The requirements and limitations of sensor networks make their architecture and protocols both challenging and divergent.

Many applications, such as large-scale collaborative sensing, distributed signal processing, and distributed data assimilation require sensor data to be available at multiple resolutions, or to allow fidelity to be traded-off for energy efficiency. I proposed the design of an adaptive cross-layered Sensor Network Architecture for enabling multi-scale collaboration and communication. This architecture enables scalability, localization and resolution-tuning, while simplifying application design by providing communication abstractions. In collaboration with a colleague, I characterized the unique design requirements for sensor network architecture and proposed *SensorStack* [6] as a suitable architecture for sensor networks. *SensorStack* enables cross-layering using a notification service, adaptability of the protocols to application-specific needs and an abstraction for data-centric communication. Next I have designed routing, scheduling and synchronization protocols to take advantage of the cross-layering and adaptivity supported by *SensorStack*.

I proposed a routing protocol [4], which is a hierarchical overlay to handle aggregation, dissemination, and multiple resolution. This self-organizing network hierarchy adapts to align with the data communication for increased efficiency. To simplify application design, I provide a set of Network Programming Interfaces to abstract the details of low-level communication and implement these interfaces efficiently in the network. For this multi-scale architecture, I have also proposed a medium access scheduling protocol [3]. This protocol takes advantage of sensor network

application characteristics such as — periodic nature of communication, limited communication abstractions, and fusion function techniques — to improve energy-efficiency. The scheduling uses a token-passing approach to provide collision-free neighborhoods for a priori known traffic, as well as provides contention-based access period for event-driven traffic. My next contribution is the clock synchronization protocol [5] which is again made adaptive for specific application needs at any time. I have proposed a scheme to convert service specifications (maximum clock synchronization error and confidence probability) to actual protocol parameters (number of messages and synchronization interval).

Physical Realization of Protocols

Simulation and physical realization are both valuable tools in evaluating ad hoc networking protocols, but neither alone is sufficient. I have co-designed a new system named PRAN (meaning “life” in Sanskrit) for implementation of ad hoc routing protocols that merges these two evaluation tools. PRAN allows existing simulation models to be used — without modification — to create a physical implementation of the same protocol. We evaluated the simplicity and portability of this approach across multiple protocols and operating systems through example implementations of the DSR and AODV routing protocols in FreeBSD and Linux using the existing, unmodified *ns-2* simulation models [8]. We illustrated the ability of the resulting protocol implementations by transmitting real-time video over a multi-hop mobile ad hoc network; a demonstration at MobiCom 2004 featured mobile robots remotely operated based on the video stream over the network from cameras attached to the robots. We also reported a detailed performance evaluation of PRAN to establish the feasibility of our proposed architecture [7].

Scalable Ad Hoc Networking

As devices with wireless networking become more pervasive, mobile ad hoc networks are becoming increasingly important. A prerequisite for such an environment is the design of scalable ad hoc networking techniques, which seamlessly integrate with infrastructure-based networks if available, and enable conventional Internet services. This scenario provided me the motivation for designing and prototyping the multi-tier wireless networks as part of Ad Hoc City and Safari projects of our research group.

In Ad Hoc City [2], the backbone network in our architecture is a mobile multi-hop network composed of wireless devices mounted on mobile fleets of city vehicles, each of which connects (possibly via other vehicles) to the nearest wired base-stations. We developed a Cellular DSR (CDSR) protocol for this multi-tiered architecture to enable general purpose wide-area communication. We evaluated our design based on traces of actual movement of a fleet of city buses in Seattle.

In Safari [1], we proposed scalable ad hoc network routing, leveraging the existing synergy with peer-to-peer networking research. To this end we developed *Masai* — a realization of the architecture — which employs topology aware, hierarchical addressing for the mobile hosts through a pro-active, self-organizing, network hierarchy that recursively groups nodes together. We developed a hybrid routing protocol that uses this hierarchy as well as performs on-demand discovery of routes. Borrowing from peer-to-peer research on lookup, we created a Distributed Hash Table (DHT) to enable fast lookup of the nodes. We evaluated this design through analysis and simulations to demonstrate the scalability of our approach.

Network Edge Architecture

My research internships at Bell Labs and Sun Labs introduced me to the challenges involved in designing high-speed edge networks. Such experiences also provided me with the necessary exposure to a typical environment of industrial R & D. During my Bell Labs internship, I designed a distributed version of the OSPF protocol to handle high load in high speed routers, taking advantage of multiple processors in the new generation of routers. During my Sun internship, I contributed in the design and prototyping of NEon — an integrated approach to architecting, operating, and managing network services. The traditional discrete approach for implementation of network services like firewall, packet classification and load balancers in tier-0 suffer from scalability and manageability problems. In a paradigm shift, NEon architecture has an integrated approach whereby all the heterogeneous network service rules are aggregated and enforced on the data packets, by a programmable enforcement device. I also developed a novel rule aggregation algorithm to generate a consistent set of enforceable rules from multiple network services, which led to a patent being filed.

References

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