RESEARCH STATEMENT

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Research Overview: My research has spanned a seeming widely diverse set of topics, with the aim of developing adaptive solutions and techniques for building communication and sensing infrastructure in wireless and optical networks. Specifically, my past researches focused on quality aware routing in multi-channel wireless-optical access networks, developing adaptive schemes in rechargeable sensor networks, while my current work lies in extending networking solutions in *challenging* environments such as building disaster recovery networks, investigating sensing and networking in pipeline environment, developing cyber-physical solutions in the fresh food logistics and smart city context etc. Some of the key highlights of my past and current research are as follows:

Energy Harvesting Wireless Sensor Networks: My dissertation research was mainly focused on addressing the strategies for achieving continuous and long-term operations of wireless sensor networks that are powered by energy harvested from renewable energy sources, such as solar. In such networks, the energy resources available at the sensor nodes varies significantly from node to node and also over time. The objective of this research is to design networking protocols that control the energy consumption at the nodes to adapt to such *spatial* and *temporal* variations of energy resources. Key components of this research include the joint power control and routing protocols, multi-channel routing protocols, adaptive duty-cycling, and event-based sampling schemes.

Disaster Recovery Networks using Mobile Sensing: In the disaster management context my main research thrust is to make use of the *WiFi Tethering* technology ubiquitously available on wireless devices, like smartphones and tablets, to set up an ad hoc network for automated data collection and sensing. I have also examined the problem of collaborative and distributed adaptation of heterogeneous set of smartphone-sensors (such as camera, microphone, gyroscope, GPS, etc.) in order to maximize the amount of useful coverage information, constrained on the individual smartphone's available battery power and sensing capability.

Urban Water Pipeline Monitoring System: I am also working on a water-flow driven sensor network for *leakage and contamination* monitoring in urban water distribution systems, where the key research outcomes are the adaptation of the network to the available energy in order to maximize leak/contamination detection, minimal artificial water circulation or leakage to improve detectability during periods of almost zero natural water flow, and the idea of *proxy sensing* techniques where the presence of certain chemical is *inferred* via easily measurable properties of the water such as pH, conductivity, temperature or depletion profile of added chlorine.

Internet of Things for Perishable Food Logistics: Recently I have started working on contamination sensing and reporting in fresh food logistics using some tiny contact and non-contact sensors that can be inserted into the shipping boxes or containers while they are out for delivery in a truck or inside the warehouse. In this context my main contribution is to propose a *magnetic communication* based sensing infrastructure in RF-challenged tissue medium and an accurate way to localize and isolate the spoiled food containers. I am also working on understanding the effect of *magnetic noise* that may arise due to the close-by conducting objects (such as truck materials) and also the possibility of *wireless energy transfer* to those energy-harvesting tiny sensors using magnetic induction in this context.

I have also started looking into several problems of content centric networks and reconfigurable data center networks using optical communications. Besides these, I did a short internship in Toyota Infotechnology Center where I worked on developing different schemes for secured Internet connection from a vehicle, using the wireless access of the charging station.

Research Philosophy and Future Plans: My research philosophy is to pick up an important real-world problem, come up with an accurate or tractable analytical model to represent the problem, then use relevant theoretical techniques to design optimal/near-optimal algorithms to solve the problem and finally, experimentally or by simulations, verify and analyze the proposed scheme. The research I enjoy is a combination of network theory and system-design, with the objective of applying these different theoretical techniques to solve problems of practical relevance in wireless or optical system design and propose practical, implementable solutions. I always prefer to work on multi-disciplinary research areas that challenges my ability to quickly adapt in new environments and make contributions. In the immediate future I would like to engage myself in (a) exploring communication infrastructure in underwater and underground scenarios where RF communication does not work well and acoustic communication is not preferred due to large latency, (b) building cyber-physical infrastructure for smart health-care for understanding the physical, physiological, psychological, social, and environment state of an individual so as to discover the causes of various diseases which can be used in the development of treatments, interventions, and prevention programs, (c) exploring Light Fidelity (Li-Fi) technology using visual light communications and its coexistence issues with the existing WiFi technology etc.

Research Proposals: During the course of my postdoctoral tenure I have also contributed to several research grants, including the winning NSF proposal (Award #1542839) on exploiting cross-disciplinary synergies between food networks and information distribution networks. I have also contributed to the NSF grant (Award #1744187 and Award #1844944) on food quality sensing and communication of food spoilage and contamination, the prediction of close-to-be spoiled food packages well ahead of time to take necessary measures (distributing them to nearby demand points, isolate the contaminated boxes) for reducing food waste, locating quickly the source of a contamination in a complex food chain etc. I have also contributed to a NSF proposal on energy management for IoT capable future smart buildings via automated control of air-conditioning, heating, fans, lighting and peripheral devices and at the same time the security monitoring by using smart camera equipment for identification and tracking, gate/door-lock management and associated equipment. These proposals are spanned towards different application areas with the motivation of interconnecting the physical-world and the cyber-world along with bringing several human factors in between.

1 Detailed Summary of My Current Research

I first summarize the different research problems that I have looked at.

1.1 Development of Adaptive Networking Protocols for Rechargeable Wireless Sensor Networks (WSNs)

This research is part of a collaborative research project with the Electric Power Research Institute (EPRI) to design and deploy rechargeable WSNs for a number of monitoring applications in power generation stations and substations. Development of effective solutions for energy harvesting from renewable resources is gaining increasing importance for achieving long term reliable operations of such wireless sensor networks. This includes energy from sunlight, vibrations, heat, magnetic field, and others. All of these sources produce the spatial and temporal variations which is the focus of this work. Our work mainly focuses on solar energy harvesting. We assume a large scale WSN that comprises of sensor nodes that are placed randomly in a given geographic area for a given monitoring application such as environmental monitoring or structural monitoring. Due to the random node placements, some nodes may be located in shadows whereas some may be receiving extended sunlight. In addition, nodes have different orientations, that affect the amount of irradiance collected by the solar panels. With the change in weather, the sun's orientation and amount of solar power intake changes as well. This brings new challenges for developing schemes considering the spatio-temporal characteristics of the harvesting technique.

We consider large-scale WSNs for data collection applications, where implementation of network-wide time synchronization is a significant challenge. Hence, it is difficult to apply synchronized duty cycling and scheduled transmissions in such networks, which are critical for avoiding energy wastage from *overhearing*. The complexity of this energy optimization problem in sensor networks arises due to the fact that it has to be addressed by *network wide* adaptations as opposed to independent adaptations at the nodes. The objective of this research is to design networking protocols that control the energy consumption at the nodes to adapt to such spatial and temporal variations of energy resources. Key components of this research include (a) the development of energy availability models for rechargeable networks which involves energy source prediction and energy storage modeling, and (b) the development of adaptive networking protocols that allow variable energy consumption where we have explored joint power control and routing protocols, multi-channel routing protocols, adaptive duty-cycling, and event-based sampling schemes. The adaptive schemes have also been tested and validated on real testbed using MICAz sensor motes [1, 2, 3, 4, 5, 6].

1.2 Water Flow Driven Sensor Networks for Leakage and Contamination Monitoring

The main objective of this project is to develop a wireless sensor network for continuously monitor water leaks and contamination and report relevant data to a control station that can do the necessary analytics for detection and localization. We consider water flow driven sensor networks that are entirely powered by water flow via a small fan unit that drives a small motor for energy conversion. We use a small super-capacitor for storing the harvested energy, primarily because of the long cycle life and high charge-discharge efficiency of current super-capacitors. The sensor node is assumed to be at pipe connection or valve points only, installed through the manholes. Its lower part dips into the water for energy harvesting and measurement of contamination, velocity, etc., and the upper part sports the energy storage, voltage booster, regulator and computing/communications unit. In particular, we assume that the upper part has a suitable wireless radio (e.g., WiFi) with antennas embedded on the exposed side of manhole covers (and perhaps sticking out if practical).

Due to the varying flow rate (water consumption rate), the availability of harvested energy varies both in spatial and temporal domains. In branch pipes, the flow rate may even drop to near zero late at night. Since the energy is constantly consumed by the monitoring node and leaks from the super-capacitor, it is necessary to have in place an artificial water circulation mechanism that can keep the system running minimally at all times. At the same time, we want to make the best use of the available energy and adapt it for low energy periods. This motivates the development of a dynamic sampling and transmission rate adaptation scheme based on individual node's energy budget. Thus, the twin objectives of the project [7, 8] are *optimal rate adaptation* coupled with an optimal mechanism for *artificial water circulation* when needed.

An interesting idea that we have developed in the context of detecting contamination in urban water distribution systems is the concept of *proxy sensing* [9]. As the potential contaminants or chemicals in a water distribution system are numerous, sensing each of the specific chemicals can be very expensive and slow since they often require taking water samples that are treated with suitable reactants, measured for specific byproducts, and then discarded. This difficulty forces proxy sensing techniques where the presence of certain chemical is inferred via easily measurable properties of the water such as pH, conductivity, temperature or depletion profile of added chlorine. Such proxy sensing, is not intended for sensing any specific type of contaminant, but can sense some aspects of the contaminant's property and thus provide either corroboration or sensing of the event at some degraded level of reliability.

1.3 Smartphone Based Distributed Monitoring in Evolving Disaster Scenarios

The world has lately witnessed several large disaster scenarios that extend over multiple days or longer, three prominent examples being the 2011 Tohoku earthquake in Japan, 2005 Hurricane Katrina, and 2011 Hurricane Sandy in the US. Such extended disaster scenarios continue to evolve, often in unexpected ways, and a situational awareness of their evolution is crucial for providing the right kind of emergency response in terms of rescue, health-care, basic necessities, debris removal, etc. Large disasters often damage the communications infrastructure, and an ad hoc emergency communications infrastructure becomes essential to cover disconnected areas. Numerous factors such as inaccessibility of the area, lack of electricity, unstable buildings, uncertainties about where the impacted people might be, etc. make it very difficult to set up such a communications network expeditiously and change its configuration dynamically so that it best serves its purpose.

It is well recognized that the ubiquitous use of smartphones and the availability of an increasing array of sensors on them can be a big boon in this regard. In particular, by making smartphone as an integral part of the emergency network, we automatically solve the twin problems of making contacts with the impacted people and gathering relevant data around them, such as their location, pictures/sounds relating to the ongoing event or the damage caused by the disaster, environmental conditions, health-status, etc. Nevertheless, integrating smartphones into the emergency network and making the resulting network cognizant of the needs of the smartphone owners, their remaining battery levels, and the physical situation around them, is quite challenging.

In order to integrate smartphones with the rest of the emergency communications network, we assume that every smartphone is equipped with our emergency networking app that is used for establishing the ad hoc network as required to fill gaps in Internet connectivity, data collection under program control from available sensors (such as camera, microphone, gyroscope, GPS, etc.), data filtering and communication to the deployed emergency communications nodes, and ultimately for changing the network configuration in response to instructions from "higher levels" in the deployed emergency infrastructure. In view of this, we propose to use *WiFi tethering* capabilities [10, 11] that are available on nearly every smartphone currently. The key idea is to use a loosely synchronized mechanism whereby the mobile phones alternate between *client* and *hotspot* mode and thereby allow support both a direct discovery and data transfer without any external access point.

Another major challenge in disaster response is maintaining flow of information, such that valuable information generated within a disaster area could be disseminated and that the impacted population could stay informed. In this direction, we proposed a situational awareness service named `StayTuned` that efficiently processes important disaster related information and disseminates it in a compressed form to the impacted population [13]. We have also developed a dynamic *spatial clustering* based approach for finding the areas of greatest need and dispatching assistance to those first, from the availble disaster-related information in an affected area [12, 14].

1.4 Internet of Perishable Logistics

Physical Internet is a fairly recent concept that attempts to revolutionize product distribution logistics by emulating the Internet. The key issues in making the distribution logistics more efficient, exible, cheaper, and more user friendly include (a) standardization of identification, labeling, packaging, transportation, tracking, etc., (b) sharing of physical distribution infrastructure among multiple companies, and (c) worker friendly logistics (e.g., enabling truck drivers to return home for the night). We have recently started looking at the synergies between fresh food networks (FFNs) and computer networks (CNs) and we found important parallels and differences between the two. One key characteristic of FFNs is the constant deterioration in quality of a food package based on the delay in the distribution pipeline and handling factors such as temperature, humidity, vibrations, etc. In CN terms, we can think of this as the case of a rotting packet, but in CNs, the packet is either good (e.g., delivered before the deadline) or useless (e.g. too late). Proper handling of rotting packets in term of routing, distribution, and end use are interesting issues for CNs inspired by food networks. FFNs also involve multiple levels of packet bundling/unbundling, which can be useful for efficient content distribution in CNs.

In this research [15, 16, 17], we want to take this analogy further and examine Physical Internet from the perspective of fresh food distribution in an well structured and advanced fashion, which we define as the Internet of Perishable Logistics (IoPL). To study the entire system in a systematic manner, we propose a layered architecture for the perishable logistics by imitating the TCP/IP network stack [18, 19]. However in contrast to the Internet architecture, IoPL needs to consider a number of additional challenges related to different resource availability (trucks, containers, load-unloading equipments), various spoilage and contamination sensing and taking appropriate actions to reduce waste, address human needs such as driver availability, their away-home time etc. When IoPL is augmented with sensors and actuators (for example contamination sensors in meat packages, road congestion monitoring etc.), the technology becomes an instance of the more general class of *cyber-physical systems*.

Another key objective of IoPL is to reduce food waste due to spoilage and contamination. Sensing of food spoilage and contamination is an active area of research, with many types of sensors currently available and under development. These tiny sensors can be inserted into the shipping boxes or containers while they are out for delivery in a truck or inside the warehouse. These sensing devices may communicate with others and with next level data integrator in the truck, which in turn communicates with the central controller. A substantial challenge here is the intra-container communication environment with tissue medium or through water-containing products (e.g., meat, fresh vegetables/fruits). In such environments, a normal RF communication (e.g., Bluetooth at the 2.4 GHz ISM band) is unlikely to be usable due to high signal absorption and complex channel conditions. Instead we are exploring a *Magnetic Induction (MI) based communication and sensing* infrastructure [20, 21, 22] in such scenarios at HF band (3-30 MHz) that is largely unaffected by the tissue medium. Compared to the RF-based techniques, the MI-based techniques have the following advantages: (a) better penetration performance (i.e., low absorption) as the magnetic permeability of tissue medium is very similar to that of air, (b) predictable and constant channel conditions, and (c) small coil antennas (e.g., a few mm or cm). Although the MI communication has a small transmission range (e.g., 1.5 m) and achieves a small data rate (e.g., 596 kbits/s), it fits well in such IoPL application.

1.5 Adaptive Routing Schemes for Multi-Channel Wireless Optical Access Networks

The purpose of this research is to explore new methods for improving the quality of communications in wireless optical broadband access networks (WOBAN). Access networks are the last mile of the communication networks that connects the telecom central office (CO) to the residential or business users. Optical (such as passive optical networks) and wireless networks (such as wireless mesh networks) are initially deployed as the access networks. Optical networks are mainly used for high-bandwidth and long distance communications, whereas wireless technologies are used for flexibility and low bandwidth uses. The present growing demands for bandwidth-intensive services and at the same time the flexibility (anytime-anywhere service) of the users are accelerating the research on efficient and cost-effective access infrastructures where optical-wireless combinations are seen as a promising approach. WOBAN is a novel hybrid access network paradigm with the combination of high-capacity optical backhaul and highly flexible wireless front-end that can provide higher bandwidth in a cost effective manner. In WOBAN architecture, optical fibers are provided as far as possible from the CO to the end users and then wireless access is provided in the front end. Because of it's excellent compromise, this WOBAN architecture enjoys lesser deployment costs because of lesser fiber costs than traditional passive optical networks.

A WOBAN consists of a passive optical networks (PON) at the back end and a multi-hop wireless mesh networks at the front end. At the back end, optical line terminal (OLT) resides in the CO and feed to multiple optical network units (ONUs) through a traditional fiber network. At the front end, wireless mesh routers form a multi-hop wireless mesh network; and a few of the mesh routers are called gateways that are attached to the ONUs. Thus if a mesh router needs to send a packet to the Internet, it has to send it to any one of the gateways and after that the packet is sent through the optical part of the WOBAN. In the upstream direction (from wireless routers to gateways), WOBAN is an *anycast* network. In the downstream (from gateway to mesh router), a gateway send a packet to a specific wireless router, thus in downstream, WOBAN is a *unicast* network. Our interest in this project is to develop adaptive routing protocols in the upstream direction [23, 24, 25, 26]. We have also explored the advantages of multiple channels and multiple radios, by designing a *joint routing and channel assignment (JRCA)* [27, 28] scheme in a multi-gateway WOBAN architecture. Extensive simulation results demonstrate potential benefits for ensuring route quality and reducing interference in multi-channel WOBAN.

2 Future Research

I next discuss the important open research problems which I plan to look in future.

WSNs for health-care: WSNs can be used in detecting the clinical deterioration of patients based on sensing and analyzing the real-time vital signs such as pulse oximetry, respiration rate, temperature etc. Some- times patients behavioral states need to be monitored that requires sophisticated machine learning techniques to detect complex conditions such as depression, stress or addiction to any drug from the sensor data available. Another application domain of WSNs in healthcare is the long-term monitoring of movements and activities of patients who are challenged with different limb movements, such as Parkinson disease or paralyzed patients. Improving the life quality of the elderly by regularly monitoring their cognitive, physical and social states can assist the caregivers in diagnosing and giving necessary medical helps and suggestions. All these can be achieved by careful integration of wireless networking, sensing and mobile computing. Exploring different techniques for medical health is one of my future research interests.

Exploring underwater and underground WSNs: The applications of underwater WSNs (UWSNs) have huge potential for monitoring the health of ocean and marine environments. UWSNs have a number of unique challenges such as limited bandwidth capacity, large propagation delay and node mobility, as well as high error probability. These bring extra challenges in localization, time synchronization, MAC design as well as forwarding schemes. On the otherhand, underground WSNs face unique challenges like high path loss which reduces the communication range of the nodes. In this scenario, exploring multi-hop routing in a large scale underground sensor networks is a major challenge. Exploring these unique challenges and developing suitable schemes to address those challenges is among my future interests.

Exploring Light Fidelity (LiFi) Technology: LiFi is a new technology which uses visible light communication (VLC) instead of radio waves. It refers to 5G Visible Light Communication systems using Light Emitting Diodes as a medium to high-speed communication in a similar manner as WiFi. One of my future interests is to study the general characteristics of WiFi and VLC (or LiFi) and to address their coexistence issues in an indoor environment to significantly improve the spectrum usage as well as the quality-of-service.

Apart from this, I am open to interesting research ideas, especially those involving multi-discipline expertise to come up with new perspectives and solutions to existing problems. Some interesting areas for my future excursion include: investigating various aspects of data-center networking, channel sensing for cognitive radios and molecular communications.

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