Research Statement

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Mobile computing and wireless networking is a young and dynamic field. Ubiquitous access to information, anywhere and anytime, will characterize new kinds of information systems in the 21st century. The global society will increasingly rely on socio-technical networks designed in harmony with societal values and economic viability, with enhanced security, privacy, resilience, availability and manageability, and the ability to incorporate as yet unforeseen technologies, applications and services. The ability to connect various components through a network will create many new applications but also many new issues, and will therefore create many new research opportunities and transform researches from various disciplines.

My goal is to do innovative and creative research that will advance the state of the art in network and computing systems. I believe network infrastructure will gradually become more robust and flexible, and enable a progressively wider variety of information services. People will communicate and access services through new network access technologies, and through a large variety of devices, including wearable devices, and non-computing sensors and actuators. Correspondingly, there will be a need for more powerful network infrastructure, for example self-managing systems that can configure and fix themselves, and the development of new network services, for example memory and computing cycle assurances to offset the limitations of low power computing devices. The ultimate goal is to make network communication completely seamless and ubiquitous. The principal challenge lies in the growing volume and heterogeneity of services, devices and access technologies, and the lack of enough bandwidth to support the exponential increase of wireless applications. This will place increasing stress on the network infrastructure, particularly wireless infrastructure, in terms of capacity, reliability, scalability and interoperability.

My approach has been comprehensive, with a combination of theoretical analysis, extensive simulations, and prototyping and measurements of real systems. My research addresses the challenges of network heterogeneity and growth in a number of different ways: 1) designing novel network infrastructure that can efficiently exploit the unused spectrum and emerging antenna techniques to significantly increase the wireless network capacity; 2) designing algorithms and protocols to address the issues due to mobility, terrain irregularity, wireless channel dynamics, bandwidth scarcity, network heterogeneity and low capacity of wireless devices to significantly improve the robustness and capability of wireless networks; 3) developing scalable, flexible and robust wireless service infrastructure to enable novel wireless applications and ubiquitous mobile computing; 4) enabling robust sensing and fusion in the presence of large volume of data, as well as data uncertainty, biases, loss and delay.

In order to address the growing complexity and fundamental challenges of the problems, the work of my group exploits theory and methodologies from a few disciplines, including signal processing, communications, network, control, optimization, computational geometry, and machine learning.

I will first summarize my research contributions, and then describe some specific research directions that I am currently working on and my past research results.

I. Summary of Research Experiences and Accomplishments

I have been conducting and leading research work in the design of network architectures, protocols and algorithms. The major goal of my research is the design of novel network infrastructures and algorithms to significantly improve the wireless network capacity/robustness/scalability, support advanced wireless applications and services, and enable seamless end-to-end high quality transmissions across heterogeneous networks.

My professional experiences are also rich. The role as a system architect and team lead in two Lucent cutting-edge projects provides me the opportunities to implement the research ideas in a real system, and learn the differences between academic researches and requirements from industrial products. It also trains my leadership and allows me to gain team work experience. The work as a research scientist in Bell-Labs allows me the opportunity to know the industrial research trend, and build research collaboration with many talent researchers in the field.

In my work in academia, I have served as PI and Co-PI for research grants in the total of 5.1 million, served as PI for 3.8 Million and my share of the funding which I served mostly as the PI/PD or PI of Stony Brook for about $3.1 Million of the total grant. I was also awarded NSF CAREER award in 2005, and Chief of Naval Research (CNR) Challenge award in 2011**.** The federal agencies that sponsor my works include NSF, ONR, AFOSR, SPAWAR and DOJ. Additionally, I was invited for talks in special workshops, industry labs, panels, and universities international wide. Together with my students, we have published over 100 journal and conference papers, including 32 IEEE/ACM transaction papers, 1 ACM MobiCom paper, 2 ACM Sigmetrics papers, 1 ACM MobiHoc paper, 1 ACM ASIACCS paper, 1 IEEE PerCom paper, 4 IEEE ICDCS paper, 3 IEEE ICNP papers, and 13 IEEE INFOCOM papers. Our publications have received over 2000 citations based on index from google scholar, and my H-index is 23.

II. On-going and Future Research Directions

A. Cognitive and Efficient Spectrum Access in Autonomous Wireless Networks

The exponential growth of wireless traffic calls for novel and efficient spectrum access techniques and wireless network infrastructures. The recent introduction of autonomous network concept, where femtocell is an application, presents as a paradigm shift from traditional cellular networks with planned deployment and centralized management to more autonomous, uncoordinated, and intelligent rollouts of small base stations deployed by end users and overlaying wide-area cellular networks. The combination of wide-area coverage to meet basic and mobile user requirements and the organic growth of small cells for hot-spot coverage and improving per-area spectral efficiency appears to be the most promising technique that can lead to multi-fold capacity increase needed for future wireless networks. Fundamentally different from conventional cellular networks or heterogeneous networks with nodes operating in different spectrum bands, femtocells are deployed in an ad hoc manner and share the same spectrum band as the cellular networks to increase the spectrum usage efficiency and allow a terminal to seamlessly operate in macrocells and femtocells. This network infrastructure, however, would create strong cross-tier and intra-tier interference.

Approaches: The objective of this project is to enable more efficient and reliable operation of autonomous femtocell networks with agile spectrum access, autonomous interference control, as well as intelligent network self-organization and self-optimization. This project has three major research tasks: 1) Investigating efficient sensing technique to effectively detect the available spectrum to use; 2) Developing distributed, dynamic and cooperative interference management schemes exploiting antenna techniques and based on sensed environmental conditions; 3) Investigating the scenarios and schemes that femtocells can be exploited to facilitate macrocell transmissions, and the potential gains in capacity, coverage and reliability. The project also develops a testbed with open source programmable wireless platforms, for prototyping and evaluating the effectiveness of various techniques developed.

To address the inter-disciplinary challenges in exploiting the scarce spectrum to achieve significantly higher transmission capacity and reliability, this work will exploit techniques across disciplines such as computer and information science, engineering, technology and applications.

Potential Impact: The proposed research has the potential to significantly increase the capacity and resilience of existing and future wireless networks. The agility and resilience of the system will also make it instrumental to support communications and applications that are important for national security and economy.

Sponsors and Results: This project is currently sponsored by NSF. Our initial results have been published in **IEEE INFOCOM'13, IEEE JSAC'14**, **IEEE SECON'15**, **IEEE DySPAN'12**.

B. Fundamental Techniques for Incentive-aware, Efficient, and Reliable Cloudlet Management and Services

Cloud computing can potentially enable performance-hungry applications on almost any mobile devices by augmenting them with cloud resources. However, running mobile applications remotely encounters a number of issues: the energy constraints of mobile devices, communication constraints due to intermittent and unreliable wireless networks, and high latency of wide-area network access. Alternatively, mobile devices can leverage nearby cloudlets (i.e., a group of resource-rich servers) through high speed local-area wireless networks where available, and use a distant cloud only when necessary. Despite the attractiveness, compared to a remote cloud, a cloudlet faces the challenge of much limited resources and more dynamic user demands.

Approaches: We will investigate a set of fundamental techniques to facilitate more efficient resource usage and reliable operations of cloudlets. Specifically, we will develop a self-adaptive Rate-dependent Bloom filter (RDBF) to exploit application caching to reduce service delay and cost. We will explore multi-dimensional pricing and resource negotiation to motivate efficient use of cloud resources for higher service performance. In addition, we will exploit matrix completion theory and learning algorithms to enable high quality while low cost cloudlet resource and service monitoring, prediction, and maintenance in the presence of unstable wireless links and user mobility.

Potential Impact: Our proposed fundamental techniques, if successful, will enable efficient, reliable and low cost mobile cloud computing and services. This will in turn support high-performance wireless applications in an energy- and resource efficient manner. The proposed research is part of a global effort in exploiting (mobile) cloud computing for advancing some critical fields for national economy and security, including health-care, transportation, smart-grid, homeland security, and education. We expect that our work will catalyze further research on cloud techniques for high performance mobile computing. Although targeted for dynamic cloudlet management, the proposed fundamental techniques can also be applied in general cloud systems, and other service management.

Sponsors and Results: This project is currently sponsored by NSF.

C. Riemannian Geometric and Stochastic Methods for Robust and High Performance Network Communications

The network becomes more complex with the increase of networked entities and their types, and the complicatedness of the deployment environment. The terrains, where the networks and sensors of military are deployed, are often non-flat and with obstacles and holes. The conventional network algorithm and protocol often fail or work at low performance in these types of terrain. In addition, the locations of communication devices or targets may often be needed while GPS or conventional localization devices are not readily available or costly to deploy. There also need methodologies to predict and improve the network performance, and detect the network problems at low cost.

Approaches: To enable reliable network deployment and functions, the objective of this work is to investigate and understand the mathematics principles underlying the predictable operation of networks and systems, and provide some fundamental methodologies and mathematical tools that can facilitate the analysis, design and management of networks. Our proposed research will specifically address the challenges of supporting reliable network operations on complex and uneven terrains. We will base our design on Ricci flow theory and stochastic process on Riemannian manifolds, and generalize these theories from smooth manifolds to networks.

To address some fundamental challenges of networks, our work integrates theories from several disciplines, including differential geometry, stochastic processes, algebraic topology, algebraic graph theory, communications, and network.

Potential Impact: Our theoretical framework and practical tools will guide the design of future network protocols and algorithms, including network deployment, provisioning and management, localization of network nodes and targets, routing, and abnormality detection. We will also develop network algorithms and protocols that leverage the tools to enable robust, adaptive and high performance network communications.

Sponsors and Results: This project is currently sponsored by AFOSR.

D. **Robust Fusion of Diverse Networked Sensing Data under Uncertainty, Biases, Loss and Delay**

Despite the growing use of networked sensors, there is a lack of advanced algorithms to efficiently process sensor data of diverse types and qualities especially in the presence of various uncertainty and communication constraints. On the other hand, work on estimation and detection in signal processing community often ignore the impact of data loss and delay as a result of network transmissions. Finally, existing studies on uncertainty and biases are mostly concerned with individual sensors, and there are very limited efforts to investigate the impact on fusion due to diversity in sensing data and biased estimates, especially under loss and delay. This work intends to obtain more accurate and timely information from networked sensing system in the presence of data diversity, bias, loss, and delay.

Approaches: We propose to use advanced filter and fuser in the fusion center to better track and process sensor data, apply information management to selectively and intelligently fuse data received for higher information gain, and actively manage sensor activities to more effectively capture information.

To achieve optimal performance in networked sensing and fusion, we integrate use of algorithms and mechanisms from statistical signal processing, optimization, communications, and networking fields. Efficient and robust estimation and fusion of diverse data from dynamic systems and uncertain environments can build a foundation for many research disciplines that deal with networked data flows.

Potential Impact: Accurate and timely detection and estimation is of critical importance to many surveillance and control applications, and these applications have significant impact on national security and economy. The proposed research is part of the global efforts in effectively handling information uncertainty to ensure reliable operation of practical cyber physical systems and efficiently extracting knowledge from massive amounts of heterogeneous data. The reliable and robust sensing and fusion paradigm will, to a certain extent, contribute to the progress of many fields such as defense, transportation, energy, and health care.

Sponsors and Results: The initial work of this project was sub-contracted from Oak Ridge National Lab from the SensorNet project sponsored by ONR. Our initial results have been published in **IEEE INFOCOM'12**, **FUSION 2012 - 2015**, **IEEE TON 2014** and **IEEE TON 2015**.

E. Integrated Control and Communications for Efficient Multi-Robot Coordination

Multi-robot systems (MRS) generally have higher efficiency, reliability and flexibility than independent robots. The performance gain of an MRS relies on the efficient coordination among robots, which in turn depends on reliable communication connections to efficiently exchange messages and data. Existing multi-robot coordination schemes generally assume the availability of wireless connections. However, it is challenging to establish and maintain connections among robots in many realistic situations, due to unstable communication conditions and the dynamic nature of robots and environments.

Approaches: The objective of this project is to investigate a set of control and communication techniques for establishing and maintaining communication connections among multiple collaborating mobile robots, in response to varying communication conditions in practice, to ensure robust and flexible multi-robot coordination. The approach is to exploit the features of wireless communications and mobility of robots to significantly increase the coverage and reliability of communications and the chance of forming communication links among mobile robots.

The integration of novel distributed control and communication techniques is exploited to enable robust and efficient communication networking, high-freedom task operation and exploration, and thus highly robust and flexible coordination among multiple collaborative robots.

Potential Impact: The results of this work potentially impact numerous applications of multi-robot systems by solving the fundamental problem of establishing and maintaining robust communication connectivity among robots, and providing a foundation to various research topics based on it.

Sponsors and Results: This project was sponsored by NSF, and we have published initial results in **IEEE TMC 2013**, **IEEE MASS'15.**

II. Previous Research Results

The research topics that I worked on can be grouped into two major areas.

The first broad area is the *cross-layer optimization and integration of network infrastructure,* with an emphasis on multi-hop wireless networks. The standardization of functional interactions between network layers has allowed developers to work independently of each other. However, we also need to better understand the interactions between the layers, for various reasons. These reasons include the need to integrate various wireless applications over the Internet, the need to reduce the redundancy between layers and thus reduce the size and weight of wireless terminals, and the growing importance of QoS and energy conservation at various layers. The object of our work is two-fold: to develop an understanding of the key cross-layer interactions; and to use this understanding to make the network infrastructure more scalable, reliable and flexible.

The second group of topics of my work can be broadly grouped into the area of *next-generation wireless network infrastructure and services*. These topics are in the areas of context-aware mobile computing and services, wireless network infrastructures supporting smart antenna techniques, and agile network infrastructure over cognitive radio nodes. Some of this work also intersects with the first area of system integration and cross-layer optimization.

A. Cross-Layer Optimization and Design of Mobile and Wireless Systems

My objective is to create infrastructure and algorithms to enable more efficient performance of the wireless system, by adopting an integrated, cross-layer approach. I had two projects in this area, developing power control and energy efficiency techniques in mobile ad-hoc networks, and building a cooperative resource management framework for an integrated radio access networks. We have investigated many specific cross-layer interactions, including the effect of lower layer control on end-to-end reliability and performance, and the effect of upper layer protocols and management on link operations. The design and optimization process combines innovations at physical layer, control and scheduling at MAC layer, efficient routing and admission control at network layer, dynamics and flow control at transport layer, and specific requirements at application layer.

A.1. Power Control and Energy Efficient Transmissions in Mobile Ad Hoc Networks

Energy conservation is critical for the success of wireless communications and mobile computing technologies. Besides conserving energy, power control is also important for minimizing interference and improving wireless transmission capacity and quality. While there has been a great deal of work on energy efficient routing schemes for ad hoc networks, our studies have shown that existing schemes normally involve significant routing overhead and path setup delay, and that node mobility can cause these schemes to have much higher energy consumption even more than that of normal routing schemes without using energy-efficient schemes. Also, existing schemes ignore energy consumption of control packets at different layers and thus tend to use non-optimal paths, resulting in a higher energy consumption and a lower throughput. Instead of only focusing on routing issues, we have derived a set of link cost models that more accurately track energy consumptions and packet errors by also taking into account factors at MAC layer and PHY layer (**IEEE TWC'06**, **IEEE INFOCOM'04**). Building on top of these models, we propose a progressive energy efficient routing (PEER) protocol that significantly reduces the energy consumption and improves the throughput with minimal control overhead (**IEEE TMC'11**, **IEEE INFOCOM'05**). The integrated support of MAC and routing for multi-channel network was presented **on IEEE TVT'10**. Our **IEEE TMC'11** paper has received more than 63 citations, and the proposed accurate energy model been used as building blocks for developing energy efficient network protocols and algorithms.

A.2. Integrated and Cooperative Resource Management over Radio Access Networks

Next generation wireless networks will need to support applications with diverse bandwidth and quality of service requirements, a mixture of real-time and non-real-time, circuit- and packet-switched services, and devices with different transmission capabilities and frequency agility. There is also a growing need to support end-to-end IP communications, to provide a universal platform for applications and devices, and for reasons of cost, scalability and reliability. However, there is a lack of fundamental understanding of the interactions and the resulting effect of resource management across different network layers, among neighboring cells, and between air interface and radio access network. System-wide implications and interactions of resource management schemes and wireless access techniques are often ignored.

The principal research objective of this project is to develop an integrated resource management framework for supporting heterogeneous traffic seamlessly over one or multiple radio access systems. Specific goals include studying the fundamental resource-allocation problems in the air interface (including 3G, 802.11, WiMAX, and Wireless PANs) and backhaul networks (with wired links or WiMAX long-range wireless links and in mesh topology for scalability and reliability), understanding and incorporating the many interactions while implementing resource management, and trading-off optimality with control and management overhead. Our work consists of the following three inter-related components: 1) Development of a holistic intra-cell resource management scheme that includes admission control at network layer, packet scheduling at link layer, and power and rate control at physical layer; 2) Development of cell load models for a mixture of circuit-switched and packet-switched traffic, and development of practical inter-cell load control and mobility management mechanisms; 3) Investigation of scalable resource management techniques for meshed backhaul networks, that particularly consider the effects of mobility on backhaul resource management, path setup and control overhead, and the reverse impact of backhaul resource control on the performance, mobility and capacity of the air interface.

I have been awarded a **NSF CAREER** award for my initiating and continuing work in this area. I have also received a grant from the department of justice (DOJ) to address interoperability issues in public safety radio communication systems. Our initial results have been published in **IEEE TMC'05**, **IEEE JSAC'05**, **IEEE ICDCS'10, IEEE IWQoS'10, IEEE INFOCOM'04**, **IEEE INFOCOM'03** [C23], and **IEEE WoWMoM'06**. Our work intends to bridge the gap between communications researches which focus on optimal air interface designs and networking researches which normally study packet transmissions beyond air interfaces. Our efforts have initiated a new research direction, and our papers **IEEE TMC'05** and **IEEE JSAC'05** have received more than 58 citations.

B. Next Generation Mobile Wireless Network Infrastructure and Services

My research group has made a set of contributions in the development of network infrastructure and services over emerging radio and computing technologies. These areas include the development of context-aware service and information management framework and the exploitation of antenna techniques for increased network capacity and reliability.

B.1. Context-aware Mobile Computing and Wireless Services

Context-aware computing involves the automatic tailoring of information and services based on the current context of the user of which the user's location is a key component. The goal of the project is to enable various context and location aware services, and to use context and location information to guide and achieve more efficient information management and distribution.

Although there are a large number of efforts in developing service management infrastructure in wire-line networks, there are very limited efforts in designing an efficient and a robust service infrastructure over wireless networks. Developing a comprehensive, working service framework over a wireless network involves a number of challenges, due to channel dynamics, node mobility, and the limited capabilities of many wireless devices. To better meet the need of future wireless applications, we have initiated the effort in developing a distributed and geographic network and service management infrastructure for scalable and robust wireless communications and services. Our system integrates a location-based information architecture to support more efficient and reliable information collection, routing and service management functions. With the guidance of locations, we have designed several stateless virtual infrastructures to significantly increase the robustness of communications and reduce management complexity.

So far, we have developed a geographic service provision infrastructure (**IEEE PerCom'07**), with efficient resource discovery, reliable service delivery, and the support of service coordination among multiple resource providers. To support efficient service delivery, we have developed two self-adaptive geographic routing protocols that can provide reliable and efficient data delivery by adapting to the service needs of applications, the variations of traffic patterns, and the change of network topology (**IEEE INFOCOM'07, IEEE TMC'12**). To enable group communications, we have designed a set of self-contained robust and scalable position supported geographic multicast protocols (**IEEE INFOCOM'07**, **IEEE WoWMoM'06**, **IEEE TMC'11**, **IEEE TC'10**). We have also received the grant from US Navy for designing network planning and management system, and NSF for developing miniaturized robotic testbed.

Sensors are important devices for capturing context information and for monitoring the environment. Resources such as power, processing speed and memory are highly constrained in sensor networks. There is a big challenge in distributing information timely while conserving energy in resource-constrained, densely populated sensor networks. Target and inquirer mobility brings further challenges to large-scale sensor networks. Many research efforts have been made in recent years trying to address one or more issues mentioned above. However, there is a lack of a comprehensive solution to optimizing the overall system performance. So far, we have designed a system architecture across MAC, network and application layer to optimize the performance of a large sensor network by taking into account the interactions and tradeoffs between different design objectives (**IEEE WoWMoM'06** [C13], **Elsevier COMNET**[J6]). The simulation results demonstrate that our system can save more than six times energy with significantly reduced transmission delay and increased data delivery ratio.

B. 2. Exploiting MIMO Technique for Significantly Higher Wireless Capacity and Resilience

With the rapid growth of wireless technologies and the popularity of wireless devices, it is very critical to develop techniques that can further improve spectrum usage efficiency. The recent advance of antenna techniques and their potential application to mobile devices bring new opportunities and also challenges. Depending on the environment and application, antenna array techniques can have many advantages, such as increased spatial reuse, higher data rate, improved reliability, higher energy efficiency, and longer transmission range. In particular, multiple-input multiple-output (MIMO) technology exploits multiple antennas at the transmitter and the receiver to improve transmission reliability and provide higher raw data rates. MIMO technique is considered as one of the most promising emerging wireless technologies that can significantly improve transmission capacity and reliability. MIMO is prominently regarded as a technology of choice for next generation wireless systems such as IEEE 802.11n, IEEE 802.16, and the third and fourth generation cellular systems. It is also being considered for peer to peer mobile applications over static wireless mesh networks and infrastructure free mobile ad-hoc networks.

Although MIMO technique has attracted a lot of attentions in recent years, there is a gap between research in communications and information theory fields which analyzes the characteristics and develops performance bound of MIMO communications, and network research which targets to enable communications between nodes and harvest the performance gain MIMO technique promises. The existing research activities in multi hop MIMO network design often provide only heuristics solutions, and the limited algorithm studies often assume very simple MIMO model by just counting the number of streams without considering the practical physical channel conditions, which not only leads to results far from MIMO's achievable performance but may also lead to failure. The heterogeneity and changes of network and channels are often ignored, which would lead to inefficient operations or transmission failures. The opportunities and requirements due to multi-user transmissions are largely unexplored in a meshed network due to the challenge of design. Due to channel fading or temporary network topology change, the channel condition could become very weak. There is a lack of strategy to handle extremely weak channel for improved transmission reliability while not significantly compromising the network capacity. Finally, existing routing protocols cannot fully exploit MIMO features to construct more efficient routing paths, and adapt network paths based on changes of environment and topology. There is also a lack of theoretical studies from the optimization perspective on the achievable routing performance by exploiting the opportunities and addressing the constraints with flexible MIMO mode selection.

We have designed integrated scheduling algorithms to fully exploit the multi-user diversity and spatial diversity enabled by a MIMO-based meshed network, to significantly improve network capacity while concurrently considering traffic demand, service type, network load, and fairness. Our results published in **ACM MobiHoc'08** and **IEEE/ACM TON** indicate that our proposed algorithms are very efficient, and can achieve up to **8** times higher data rate and **90%** lower delay as compared to conventional MIMO schemes. The proposed cross-layer algorithms reduce the gap between theoretical studies in the physical layer and practical implementation in network environments, and thus improve wireless network capacity and performance. We have performed further designs to adaptively exploit both diversity and multiplexing to coordinate transmissions in heterogeneous MIMO networks, where nodes have different antenna array sizes with paper published in **IEEE MASS'09 and IEEE TMC'14**, and demonstrate the potential of exploiting of MIMO nodes as relays to significantly improve the network performance (**IEEE MASS'10** and **IEEE TC'13**) and in forming high performance network topology **(IEEE ICDCS'12**). Our work on theoretical upper bound of MIMO-routing gain published in **IEEE INFOCOM'10** has received a lot of attentions. Our initial work in IEEE TON'10 has received more than 78 citations and motivated many follow-on studies on developing efficient MIMO schemes in distributed networks.