RESEARCH STATEMENT

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Wireless communications has changed the way we live, work, and learn, and the demand for wireless communications with high speed and ubiquitous connectivity continues to increase rapidly. Currently, a variety of wireless networks, e.g., cellular networks and wireless local area networks, coexist and support a broad range of mobile services. Meanwhile, many new types of wireless networks are still being developed to meet the needs of emerging applications with new communication requirements, such as cognitive radio networks and wireless sensor networks. When designing these networks, not only is it important to realize the desired functionalities for new applications, but also it is crucial to investigate how to achieve the optimum bandwidth and energy efficiency, due to the scarcity of the respective resources. This investigation requires an interdisciplinary effort that encompasses areas of signal processing, communication, control, and information theory.

Through information-theoretic research, we wish to find the fundamental limits of a network, and develop new network designs that ultimately achieve these limits. This not only will have an impact on the design of future wireless networks, but also can help to solve issues with current wireless networks. An example is the AT&T 3G wireless network: as Apple iPhone users began running bandwidth demanding applications such as multi-media streaming, the network became overloaded such that the users would experience very slow speed and frequent connection drops. The first natural question is whether the current design of the wireless network is optimal. If not, what is the fundamental limit on the performance improvement that can be achieved? And, how can this be achieved at minimum cost?

My research has focused on network information theory, which provides partial answers to the above questions. Specifically, I have studied a number of fundamental building blocks of a network, including relay channels, broadcast channels, and interference channels. Without a thorough understanding of these elementary network models, it is not possible to fully understand a general communication network, which can be large and arbitrary. The main objective of my research is to investigate how information can be more efficiently communicated over these network models and their variants in a set of different network scenarios. In the following, I list several of my key contributions in these areas.

* Cognitive Radio Networks

The entire available wireless spectrum ranging from 3 KHz to 300 GHz is currently divided into many small non-overlapping bands, which are licensed for different communication purposes, such as mobile communication, TV broadcasting, satellite communication, maritime communication, etc. This leaves little room to allocate new isolated bands for new communication systems and applications. However, measurements show that most of the allocated spectrum is vastly under-utilized at any particular location and time, especially over the TV bands. Cognitive radio has emerged as a new technology that can substantially increase spectrum utilization efficiency by allowing secondary users (unlicensed users) to share the spectrum with primary users (licensed users) as long as the interference caused is maintained below a certain prescribed level.

An information-theoretic model has been proposed to study the fundamental limits of cognitive radios. In this model, one primary user is sending information to its receiver, while a secondary user is allowed to communicate with its own receiver simultaneously over the same
band of spectrum. My work on cognitive radio is mainly concerned with how a cognitive user can utilize its knowledge about the primary user to achieve better transmission rates for itself as well as for the primary user. I developed a coding scheme that effectively integrates cooperative communication techniques (super-position coding) with interference mitigation and exploitation (rate splitting and dirty paper coding) to achieve the best transmission rates among all prior techniques in the high interference regime.

Recently I have successfully addressed incorporated broadcasting techniques as well. Specifically, the new coding scheme stems from viewing the cognitive radio channel as a variant of the broadcast channel instead of the interference channel. The new achievable rate region is to date the largest among all existing work on the cognitive radio channel. In addition, I also worked on causal cognitive radio channel, and proposed a coding scheme combining relaying techniques with interference management to achieve the best transmission rates to date.

**Wireless Sensor Networks**

Wireless sensor networks have drawn significant research interest in the last decade, primarily due to their broad range of potential applications. For example, a large number of sensors can be deployed over the battlefield to detect enemy intrusion instead of using land-mines. A wireless sensor network usually operates using batteries, and thus a key design issue is how to communicate effectively with minimum energy consumption. To seek the solution, my research investigates effective communication strategies to achieve the best communication rates given limited power at each network node.

Consider a multi-hop wireless sensor network that is deployed over a battlefield to monitor the movements of heavy weapons. Two neighboring sensors should have a correlated observation of the same event. They may convey their individual observations independently to two neighboring sensors for relaying, but this approach is not efficient in terms of power consumption. In fact, my work shows that the correlation between observation inputs offers a great opportunity to save transmission power if the neighboring sensors cooperatively transmit the correlated information. Specifically, I investigated the interference channel with common information, where correlation between the two source inputs is in the form of common information. I proposed a coding scheme that consists of three layers: a cooperation layer regarding the common information, a collaboration layer regarding the crossly observable information, and a private layer. The resulting achievable rate region leads to strict improvements over the existing results in the Gaussian case, and demonstrates optimality in certain special cases.

Due to the inherent broadcasting nature of wireless transmissions, feedback can be easily collected at sensor nodes that are capable of receiving. It has been proven that feedback does increase the capacity of multi-user channels (in contrast to the point-to-point channel case). However, the capacity regions are unknown for most multi-user channels with feedback, except for a few special cases with noiseless feedback. With the objective to improve the transmission rates by exploiting feedback in wireless sensor networks, I have studied interference channels with noiseless feedback, and relay channels with generalized (noisy) feedback. The main idea is to extract common information from the feedback, which enables cooperation between transmitting nodes to achieve higher transmission rates. The benefits of feedback (even generalized feedback) can be easily seen from our results by considering the asymptotics. However, the general optimality of our results is still unknown. I believe inducing common information to achieve cooperation between transmitting nodes is not a general solution to exploit feedback. A general
form of cooperation inducible from the feedback may exist, which I plan to pursue in my future research.

* **LDPC Coded MIMO OFDM Systems**

Besides information-theoretic work on wireless communication networks, I have also had hands-on experience in communication system design, particularly the low-density parity-check (LDPC) coded multiple-input multiple-output (MIMO) orthogonal frequency-division multiplexing (OFDM) system. I proposed a simple decoding technique called bypass decoding for LDPC coded MIMO OFDM systems. In the proposed decoding technique, a codeword is decoded in two steps based on the log-likelihood ratios (LLRs) of the coded bits: First, the hard decisions are made on the coded bits whose LLRs have magnitudes above a certain threshold. Next, the rest of the coded bits are decoded by using an iterative receiver that remains structurally the same as the conventional receiver, but adapts to the number and the locations of coded bits decoded in the first step. I implemented the LDPC coded MIMO OFDM system in software to simulate the system with different combinations of symbol detection algorithms (MAP or sphere decoding) and LDPC decoding algorithms (full message passing or the proposed bypass decoding). Our simulation results confirm that, compared with the conventional decoding approach, this decoding technique not only delivers a considerable reduction in decoding complexity, but also maintains a comparable performance as long as the threshold is properly chosen.

**Future Directions**

I plan to further investigate communication networks from three different perspectives: theory, practice, and application. I believe practice and application not only allow us to verify theories, but also can help to discover limitations of existing theories and inspire development of new theories. Below I highlight three topics which I wish to work on in the near future.

* **Exploiting Feedback and Correlation**

First, I would like to continue my current research in network information theory, with a specific focus on understanding two inherent properties of most wireless networks: feedback and correlation. I believe that the grand problem of finding the capacity of an arbitrary wireless network cannot be solved without a thorough understanding of these two properties. Existing work on these two is relatively limited. In particular, almost no capacity results have been reported for multi-user channels with correlated sources, and very few capacity results have been established for multi-user channels with feedback. I plan to perform an in-depth study on the structure of correlation and find out what forms of correlation are inducible from feedback, by applying more sophisticated tools from statistics. The research output is expected to have a broad range of potential implications. Firstly, it may help to develop new coding schemes to convey correlated sources in a network, and may solve open problems associated with correlated sources, such as multiple access channels with correlated sources, broadcast channels with correlated sources, etc. Secondly, it may answer the questions on how to effectively use various forms of feedback: noisy, quantized, or perfect, and how to select the best form of feedback if finite rate of feedback is allowed. These are crucial intermediate steps towards a complete information-theoretic understanding of communication networks.
Practical Code Designs for Cognitive Radio Systems

I plan to apply the theoretical insights gained through my past work to practical design of cognitive radio systems. As discussed earlier, cognitive radio is a promising candidate for future wireless technologies, but there are still many implementation issues to be addressed. One key issue is the code design for the cognitive radios. In order to mitigate the known interference, the cognitive user needs to apply a particular coding technique called dirty paper coding. So far, there exists no simple implementation of dirty paper coding to fully capitalize the performance gain of this coding technique. One of the existing implementations is using lattice codes, exploiting the fact that lattice codes are both good channel codes and good source codes. The performance of this implementation is good, but the complexity is very high. I plan to investigate low-complexity alternatives to lattice codes that provide a flexible tradeoff between complexity and performance. Through this research, I expect to gain a better understanding of the complexity issue involved in cognitive radio systems. I would also like to find out how much theoretic performance can be actually retained with a practical code design of moderate complexity.

Network Design for Smart Grid

With both theoretical and practical experiences in communication network design, I plan to study the smart grid, which can be regarded as a great future application of communication networks. The smart grid is an emerging paradigm in the power industry. It aims to replace the current hierarchical, centrally-controlled, and broadcasting grid structure with one that is more distributed, more robust, and more efficient. One interesting key capability of the smart grid is that it can easily integrate distributed power generation with renewable sources such as solar and wind into the grid. For example, a customer can not only consume power from the grid, but also sell back to the grid the power generated with his own solar panel. The intelligence and the distributed control mechanisms for these exchanges must be built upon an infrastructure that is extremely robust and enables sufficient information exchange. To this end, there are many questions to be addressed. For example, do we need to build a whole new communication network for the entire grid? Can we implement the associated communication network as a sensor network? If so, how can we modify the existing sensor network design such that it can support real-time and low-rate communications with extremely high reliability and security? Apparently, all these issues cannot be addressed without an interdisciplinary effort from areas like control, communications, and signal processing. Hence, I would like to establish a collaboration with future colleagues from the respective areas to explore these problems. The research on smart grid is still in its early stage, and I believe the impact would be significant.

In the long run, I would like to further develop my expertise and extend my current research in information theory and wireless communications. The objective is to build a better understanding on how information can be optimally communicated over a network in terms of speed, efficiency, and reliability. I would also like to expand my research beyond the scope of communication networks, by applying my expertise in information theory and wireless communications to new areas such as smart power grid design, bio-informatics, etc.