CSoI Tier I seed grant proposal:

Understanding Information-Energy Interactions

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I. Background and problem statement

A. Background

In modern systems, energy interacts with information in myriad ways. For instance, in near-field communication (e.g. cochlear implants, RFIDs) is used to send information as well as power on the same link; in indoor communication, circuits that process information consume significant amount of power; in energy-harvesting systems, transmitters and receivers harness the power available in the environment. And even in natural systems, such as the human brain, energy is used not only for communication, but also for processing information within a system.

Shannon's fundamental results bring forth an interaction between information and energy. For instance, consider the famous formula

$$C = W \log(1 + SNR), \tag{1}$$

where C is the channel capacity (the maximum achievable rate for reliable communication), W is the channel bandwidth, and SNR is the ratio of the received power and the noise variance.

Are all of the ways of energy-information interaction captured by the Shannon's capacity-formula? Simply looking at the examples we discussed in the beginning, the answer is *no*! Traditional information-theoretic formulations only capture one aspect of one component of the system energy: the use of transmission power to transmit information. Not only are their more aspects to transmit power (e.g. it can be used to transmit informatino and power), it is not the only component that consumes power (e.g. information processing at the transmitter and receiver also consumes power).

We believe that understanding these interactions is a tremendous opportunity for information-scientists to expand the scope of traditional information theory. Our goal is to understand these questions by focusing first on *experiments*, and then abstracting the relevant aspects to formulate and address fundamental questions.

B. Problem statement

While the entire area of information-energy interaction is of interest to us, we have concrete problems that we intend to look at in the near future. These are:

- **Energy in communication and computation**: Building on earlier primarily theoretical work [1], [2], [3], we intend to pursue three directions:
    1) **Error-correcting codes that attain minimum *total* communication power**: Our fundamental results [3] show that the schemes that attain minimum total power (which includes power consumed in wires and computational nodes at the encoder/decoder) operate at a substantial gap from the fundamental Shannon limit on transmit power. Our goal in this part is to find explicit constructions of codes that minimize the total power.
    2) **Minimizing energy in computing the Fourier transform**: Recent results from Dina Katabi's group [4] show that the Fourier transform can be computed with significantly less Turing-complexity if the observed signal is *sparse*. The fundamental question we seek to address is: is this advantage retained when we consider the complexity in simple circuit models? In particular, is the popular butterfly structure of computing the Fast Fourier Transform still optimal? Our recent circuit-complexity results on recovering sparse signals could offer insights on the question. The question also connects directly with tradeoffs between costs of compression and analysis listed in the "Grand Challenges" report.
    3) **Improving fundamental limits on total power**: The fundamental bounds established in [2], [5], [3] do not account for the time required for a signal to propagate on a wire. The effect of wire-delays could be significant, because fundamentally, the wire-lengths must increase [5] as the target error probability is driven to zero. Precise modeling of time required for wire-propagation using laboratory experiments will be performed, and then new fundamental results will be derived for these models.
- **Wireless information and power transfer**: Can one extract information and energy from the *same* signal? The question combines fundamental ideas developed by Shannon in information transfer with those of Tesla in power transfer. It is of immense interest in biomedical implants, such as the cochlear implants and the pacemakers. We seek to address this question using two approaches:

1) **Implementation**: We seek to implement a receiver circuit that extracts more information and power from the same signal than what is possible with two identical circuits, each of which extracts information and power from two different signals.
2) **Theory**: Do laws of physics fundamentally allow for extracting information and energy from the same electro-magnetic signal? If so, what are the fundamental tradeoffs? The answer will likely require using a combination of tools from statistical mechanics, electromagnetics, and information theory.

II. Proposed Activity

We seek to bring together our respective expertise — Pulkit's in information and coding theory, and Karthik's and George's in circuits — to ask these fundamental questions from a practically-relevant standpoint.

This proposal will require frequent interaction among us. Pulkit and George are both located at Stanford University until January, 2013 (at which point Pulkit will join Carnegie Mellon University), and Karthik is located at UC Berkeley, which is nearby. Until January, therefore, our physical locations will allow for weekly meetings. After January, we plan to have virtual meetings every two weeks. We also intend to spend two weeks at Carnegie Mellon for closer interaction.

We will use collaboration tools available through `soihub.org` to hold virtual meetings as well as give talks as student brown-bag seminars introducing the rest of the CSoI community to our ideas and goals.

III. Expected Outcomes and Timelines

Since this is a Tier I proposal, our goal is to bring together our respective knowledge areas and obtain preliminary results that will enhance our Tier II proposal next year. Specific outcomes are:

- **Short Term Outcomes (six-eight months)**
  1) Understanding wireless power transfer: George's current work explores circuits for wireless power transfer, with emphasis on securing such systems. We will develop a parallel understanding on optimizing these circuits for power transfer by familiarizing ourselves with the related literature.
  2) Circuit implementations/simulations: In the first part of the project, we seek to bring together our respective expertise to implement circuits for improved modeling of encoding and decoding. This is a continuation of a project that Karthik has been leading at Berkeley, in collaboration with Prof. Jan Rabaey.
  3) Which are the "greenest" codes?: This part of the project brings together Pulkit's expertise in coding theory with Karthik's and George's expertise in circuits. We ask the question: which of the existing codes minimize the total power? This requires modeling power consumed for various codes using simplistic circuit simulations.
- **Long Term Outcomes (eight months or more)**
  1) Tier II proposal on fundamental information-energy interactions: While the focus in the first part is to get a preliminary understanding and circuit implementations, we seek to formulate precise fundamental questions at this intersection addressing which can have far-reaching consequences in short-distance communication as well as medical implants.
  2) Publications: The team will immediately start working for developing early results that would add to a working paper at Allerton conference, October 2012, on codes that attain minimum total power. The next two papers will bring in the issue of information and power transfer, and will be submitted to appropriate conferences (ISIT and/or circuit/CAD conferences).

IV. Proposed Work Statement

Because Karthik and George have their expertise in circuits, and Pulkit's expertise is in theory, Pulkit will lead the work for understanding the strategies to use for each circuit. Karthik and George will then lead the implementation of these strategies. The three of us will then work together on the theoretical formulations and solutions.

We intend to meet in person on a weekly basis until Pulkit's departure to Carnegie Mellon. Following that, we intend to have a two-week period when Karthik and George visit Pulkit. The goal would be to have circuits for "green" codes and decoders, as well as wireless information and power transfer, running by March 2012. These circuits will allow us to formulate more concrete fundamental questions.

REFERENCES

[1] P. Massaad, M. Medard, and L. Zheng, “Impact of Processing Energy on the Capacity of Wireless Channels,” in *International Symposium on Information Theory and its Applications (ISITA)* 2004.

[2] P. Grover and A. Sahai, “Green codes: Energy-efficient short-range communication,” in *Proceedings of the 2008 IEEE Symposium on Information Theory*, Toronto, Canada, Jul. 2008.

[3] P. Grover, A. Goldsmith, and A. Sahai, “Fundamental limits on the power consumption of encoding and decoding,” in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Jul. 2012.

[4] H. Hassanieh, P. Indyk, D. Katabi, and E. Price, “Nearly optimal sparse fourier transform,” *CoRR*, vol. abs/1201.2501, 2012.

[5] P. Grover and A. Sahai, “Fundamental bounds on the interconnect complexity of decoder implementations,” in *Conference on Information Sciences and Systems (CISS)*, Baltimore, MD, Mar. 2011.

V. BUDGET AND JUSTIFICATION

Budget section removed.

VI. RESEARCH STATEMENTS

A. Pulkit Grover

My recent work deals with understanding circuit-complexity for circuits in a 3-D world on encoding and decoding in wireless communications. The traditional computational models — such as the Turing machine model and the traditional models for circuit complexity — do not constrain the communication to be performed in three dimensions. Simultaneously, obtaining lower bounds on Turing or circuit complexity of problems has proven to be extremely difficult. This is partly the reason that fundamental complexity lower bounds did not exist on encoding and decoding for coding techniques in information theory. My work derives fundamental lower bounds on wiring complexity of encoding and decoding error correcting codes by making explicit assumptions on 3-D modeling of computation. In this proposal, we're hoping to extend these ideas to obtain stronger fundamental bounds and experimental validation for total power consumption; as well as a fundamental understanding ofi ssues in information and power transfer. I personally benefit as well because I get to learn about practical circuit constraints, which I believe can lead to new fundamental problem formulations.

Pulkit will serve as a center postdoc advisor for this project.

B. Karthik Ganesan

In my research, I am helping develop a novel approach towards the joint-design of power-efficient channel codes and decoders. In our work, we take a joint theory-practice approach to this problem. Using fundamental bounds on encoding and decoding power as a guiding principle, we develop circuit models for the power consumption of different decoding implementations. This involves the design, layout, and simulation of decoders in CMOS and extending these simulations to model larger classes of codes and decoding algorithms. We then use these models to search for codes that can minimize the total power of communication systems at different error-probabilities and path-losses. Our hope is that this modeling approach can help designers choose optimizing codes and corresponding decoders with additional insight and guidance.

In separate research, I am also helping develop stochastic geometry models of transportation networks. The theoretical part of this research develops a set of mathematical axioms for random networks on points in the plane to satisfy exact scale-invariance as well as rotation and translation invariance. These axioms define a new class of stochastic processes called scale-invariant random spatial networks, and the theory suggests a nice set of summary statistics for this process (analogous to how entropy rate summarizes the behavior of stationary, ergodic processes). Several concrete models have been rigorously proven to satisfy these axioms, including one based on minimum-time routes in a binary hierarchy of roads with different speed limits, and additional constructions based on Poisson line processes and dynamic proximity graphs. There is also a simulation aspect of this research, which involves simulating these stochastic processes and generating data and graphics. These simulations help us verify the properties of these constructions which make them plausible models for real-world networks.

C. George Alexandrov

George has recently joined Andrea Goldsmith's group at Stanford as an undergraduate student. As a part of a summer project, he implemented a simple system for wireless power transfer and eavesdropper detection. The basic idea is to use Maxwell's equations to detect the presence of an eavesdropper by measuring the change it introduces into the transfer functions. George hopes to learn information theoretic tools and techniques in order to understand the issue of simultaneous information and power transfer more deeply.