Understanding information-energy interactions

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I. Our obsession: information-energy interactions beyond Shannon's capacity formulation

Shannon theory explored one information-energy interaction: that between transmission energy (SNR) and information-communication-rate (capacity C) exemplified by the famous formula $C = \frac{1}{2}\log(1 + \mathrm{SNR})$.

But there are information-energy interactions that go beyond Shannon's formula, and those are the interactions that interest us. The interactions we are currently studying are:

1) Fundamental limits and achievable strategies for minimum energy required in **transmitting and processing** information.
2) Understanding **"Informational-Friction" that quantifies energy expended in *moving* information**.
3) Understanding **Maxwell's demon**: a paradox in physics and information, and through it, the connection of the Second Law of Thermodynamics and statistical entropy with Shannon's entropy.
4) Fundamental limits and practical implementations of **simultaneous information and power transfer**.

II. Progress/Insights

A. Informational friction and fundamental limits on energy consumed in computation

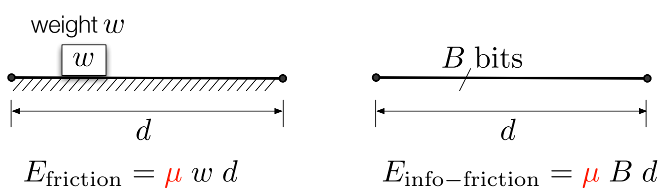

Fig. 1. The model for energy in information-friction is analogous to classical friction. Instead of moving a mass, a "mass of information" is moved from one point to the other. The information-friction model applies to communication across circuit wires, optical fibers, and even moving a stored memory physically from one point to the other.

1) **"Informational friction"** exists (see Fig. 1). Surprisingly, this frictional loss has been ignored in computer science, physics, and even in information theory. Taking it into account in computation at the encoder/decoder yields new fundamental limits on *total* (transmit + computation) energy consumed in communication. The results appeared in the proceedings of ISIT'13 [1] [1], where Pulkit presented them (and are being polished for a submission to IEEE Trans. Info Theory.).
2) Our new results provide fundamental limits on informational-friction energy consumption in **computing the Fourier transform**, the (perhaps) most widely used signal processing function. Results on energy requirements for **computation of BigData functions** are also in progress.
3) Our results (presented at **Allerton'12** [2] by Pulkit), present lower bounds on wire-lengths in decoding computations.[2] We recently obtained stronger bounds which allow us to relax some assumptions we made about the decoding circuitry in the Allerton paper and we also obtained new *upper* bounds on the wire-length.
4) Closer to practice, our results (presented at **Globecom'12** [3] by Karthik), present detailed models of computation for realistic estimation of energy consumed in decoding circuits.
5) More recent results (**in preparation for submission to IEEE Trans. on Wireless Comm.**, led by Karthik) obtain upper bounds on wire lengths of LDPC decoders (i.e., decoders for a class of codes that performs well and yet is reasonably easy to implement in parallelized fashion).

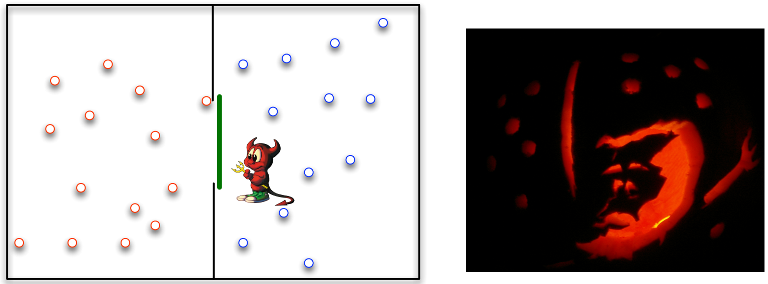

Fig. 2. Maxwell's demon, a classic paradox in physics [4] that connects information and energy via the Second Law of Thermodynamics. On the right is Pulkit's halloween pumpkin from Oct '12 with Maxwell himself represented as a Maxwellian demon.

B. *Maxwell's demon and the Second Law of Thermodynamics*

Maxwell's demon is a classic paradox in physics that does not yet have a single unanimously accepted solution. Bennett and Landauer's solution is the most widely accepted [4] today, and it yields fundamental limits on energy of computation. The conclusion is very surprising: reversible computation can be carried out with *zero* energy [5]. But the key conclusion is that erasure of any bit of information during computing costs $kT\log_e(2)$ bits of energy *because erasure reduces system entropy*. But why must reduce in entropy cost energy? Because that's precisely what the Second Law states! It is this connection between information and energy that has been of interest to physicists and information theorists (including Tom Cover).

Our goals here are:

1) There are subtle differences in the usage of the term "entropy" between information theorists and physicists, and our goal is to understand and attempt to bridge the gap between the two.
2) We believe that an approach that incorporates 1) Friction; 2) Noise; and 3) Delays, in computational networks, will help develop an understanding that is simultaneously fundamental and relevant.
   Our recent results [6], for instance, extend our understanding of information friction to situations when the computation needs to be executed in finite time (unlike in the physics-based understanding). Karthik and Pulkit have discussed ideas on how to incorporate delays in computing, but we have not arrived at a concrete formulation of the problem.

C. *Wireless information and power transfer*

Current wireless technologies (both in far field and near field) use energy harvesting schemes to leech power from a source. However, there are few, if any, circuits that are able to leech energy while maintaining information transfer. Because these two schemes compete directly in terms of the circuit parameters needed, most designers choose to separate their functionality entirely. Our goal is to study the intellectually and practically relevant issue of harvesting information and energy from the **same** signal.

1) We now have *preliminary implementations* of system-components that will allow us to **simultaneously transmit information and power wirelessly**. Further implementation is in progress. Three undergraduate students at CMU have joined the effort.
2) Power transfer requires high resonant peaking at one particular frequency for maximum efficiency (high "Q-factor" of the circuit, minimal bandwidth), but information transfer cannot be achieved at one frequency since a single frequency cannot carry any information. Information transfer requires a larger bandwidth and in effect a smaller Q. We (led by Rahshel Brown and Ana Beisy Cruz) are studying these tradeoffs from a circuit as well as theory lens.
3) We are also studying coding techniques (e.g. sending more 1's than 0's) in order to send power while communicating information.

[1]Part of these results were presented at Information Theory and its Applications (ITA) Workshop in San Diego, Feb. 2013.
[2]These results were the first results obtained with the support of the CSoI seed grant.

III. Meetings convened

Meetings were frequent (once a week or more beween Karthik and Pulkit, once every two weeks (until March 2013) between George and Pulkit), in person (often supported by CSoI seed-grant funds) and via skype/phone:

1) Currently, Pulkit and Karthik are speaking over phone/skype and communicating over email. They are working together to prepare a journal paper that combines their earlier results from Globecom '12 and Allerton '12 in both theory and circuits, with some stronger results that they have obtained since then.
2) Karthik visited CMU from March 26, 2013 - May 1, 2013 to work with Pulkit. During this time period, they met and worked every day and obtained several new results (which they are currently writing up as part of a journal paper) and had some discussions about fundamental limits on energy required for *reliable* computation. They also designed and help facilitate a course project in an integrated circuits class (ECE-18-340) taught by Shawn Blanton (faculty, circuits, CMU). Students designed different 4-bit message passing decoders, and we collected their simulation data with the hope of modeling it to understand decoding better.
3) From Jan '13 - March '13, Pulkit, George, and Karthik meet bi-weekly (and sometimes more frequently) over skype/google-hangout.
4) Until Jan '13 (when Pulkit joined CMU), George and Pulkit met on a bi-weekly basis to design circuits for information + power transfer.
5) For Globecom'12 paper presentation (Dec '12) and soon after, Karthik and Pulkit met multiple times discussing ideas on information power transfer.
6) For Allerton'12 paper and soon after, Pulkit and Karthik met frequently (Sep. 15, Sep. 19, Oct. 17, and daily in the week of Sept. 23-29) and formulated and solved problems on upper bounds on wiring lengths [2]. Many of these discussions were with Andrea Goldsmith (CSoI faculty, Stanford). Karthik and Pulkit have been talking to each other over phone/skype at least weekly since then.

Some of our early meetings are documented on: https://sites.google.com/a/soihub.org/info-energy/home?pli=1

IV. Papers, Posters, and Presentations

Papers under review for conferences: A paper [1] has been submitted to ISIT '13, and Pulkit plans to present his results there (pending acceptance of the paper). (Possibly already published, maybe Pulkit can update)

Papers in preparation:

- IEEE Transactions on Wireless Comm. '13: Combining results from Globecom '12 and Allerton '12 with new results that we obtained during Karthik's visit to CMU. The hope is for this paper is to present our most mature understanding of the energy required for transmitting and processing information, encompassing ideas from both circuit simulations and theory. Plan is to submit this sometime in September.

Papers Published:

- Globecom '12: on energy consumed in communication circuits.
- Allerton '12: on informational friction and energy consumed in various computations, including decoding, encoding, and Fourier transforms.

Presentations and Posters:

- ITA '13: Talk about new fundamental limits on *total* (transmit + computation) energy consumed in communication obtained via consideration of informational-friction.
- ICCAD Workshop on Analog/Mixed-Signal CAD '12: Poster emphasizing energy required for data-conversion of coded information
- Pulkit also presented the work in seminars at CMU, IIT Bombay, Tata Institute of Fundamental Research (Bombay), LNMIIT (Jaipur, India), and will present two seminars at IIT Delhi, and National Brain Research Center (New Delhi, India) in early September.

Media coverage:

The work, along with an acknowledgement of the CSoI seed grant, were featured in a press release at CMU: http://www.cmu.edu/news/stories/archives/2013/june/june28_pulkitgrover.html

V. Plans for team meetings

Planned Team meetings:

- Pulkit will likely visit Berkeley in late September 2013. During this time, Pulkit and Karthik will meet and work on polishing the journal paper, and will discuss ideas with George. We will schedule meetings with Jan Rabaey and Andrea Goldsmith in order to discuss the paper and present our new results.
- Karthik visited Pulkit at CMU in March and April '13 (for a period of $\sim$ 40 days).
- Pulkit and George continued bi-weekly meetings over phone/skype, but the meetings have stopped now that George is in Berkeley and is focusing on other things.
- We have involved three undergraduates at CMU in these discussions and implementations of wireless power and security, namely Rahshel Brown, Max Regan, and Ana Beisy Cruz. They all have preliminary results on wireless information and power transfer, and securing information against probing attacks via investing additional energy.

VI. Individual experiences and benefits of this collaboration

This work has been a tremendous benefit to those involved. This collaboration and the association with CSoI helped George and Karthik during their graduate school application process this past year. Both received admission to and accepted offers from CSoI graduate schools. In the fall, George will attend UC Berkeley, and Karthik will attend Stanford (thus they will switch between their undergraduate CSoI schools)!

For Pulkit, Karthik's CMU visit helped him instigate interest in his students in energy-information interactions. Continued collaboration with CSoI has also been helpful to him in discussing ideas with the CSoI faculty at various conferences and meetings, and get their feedback.

VII. Publications that came out of this grant

Publications [1]–[3] resulted from interactions we had over the past twelve months. Journal publications [7], [8] and a conference publication [6] are works in progress.

VIII. Continuation for another year

We would like to continue this collaboration for another year and receive another round of funding. In the spirit of our involving undergraduate students, it would also be great to add Rahshel Brown, Max Regan, and Ana Beisy Cruz, undergraduate students at Carnegie Mellon University, to our group who will be helping understand information-energy interactions through wireless information and power transfer (and exploring inductive coupling in general).

IX. Additional Comments

We found the web-interface to record meetings helpful in the beginning, but as we got busy, we could not find time to update it. Also, our frequent in-person team-meetings meant that our interactions were fairly close in time, the web-interface, as helpful as it was, did not need to be updated.

References

[1] P. Grover, ""Information-friction" and its impact on minimum energy per communicated bit," *IEEE International Symposium on Information Theory (ISIT)*, 2013.

[2] K. Ganesan, P. Grover, and A. Goldsmith, "How far are LDPC codes from fundamental limits on total power consumption?" in *Proceedings of the Allerton Conference on Communication, Control, and Computing*, Monticello, IL, Oct. 2012.

[3] K. Ganesan, Y. Wen, P. Grover, A. Goldsmith, and J. Rabaey, "Choosing "green" codes by simulation-based modeling of implementations," in *IEEE Global Communications Conference (Globecom)*, Anaheim, CA, Dec 2012.

[4] H. S. Leff and A. F. Rex, *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing*. Insitutite of Physics, 2003.

[5] R. Landauer, "Irreversibility and heat generation in the computing process," *IBM journal of research and development*, vol. 5, no. 3, pp. 183–191, 1961.

[6] P. Grover, "Faster computing requires moving information to larger distances," *in preparation*, 2013.

[7] K. Ganesan, Y. Wen, P. Grover, A. Goldsmith, and J. Rabaey, "New upper and lower bounds on total (transmit and circuit) power consumed in communication," in *in preparation for submission to IEEE Trans. Wireless Comm.*, 2013.

[8] P. Grover, ""Information-friction" and energy consumed in computation and communication," *in preparation for submission to IEEE Trans. Info. Theory*, 2013.