Outline:

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"Time-Division Multiplexing for Green Broadcasting"
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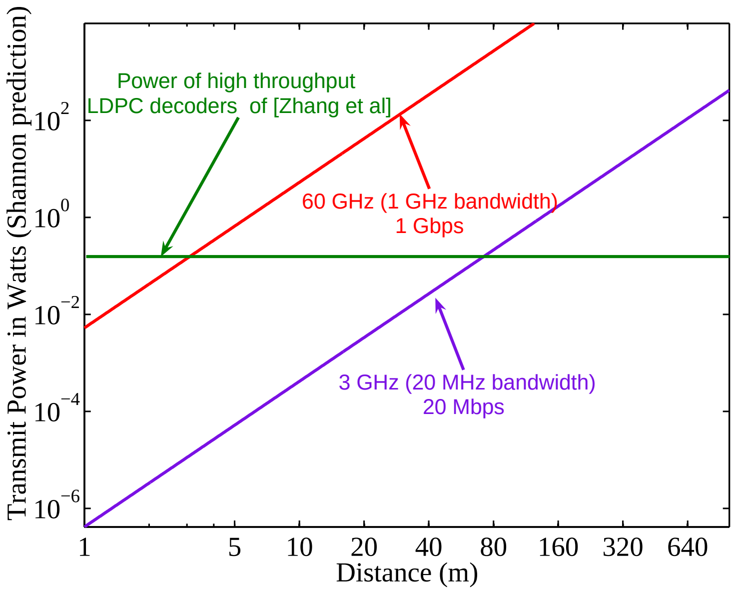
Slides available: www.eecs.berkeley.edu/~pulkit/ISIT09Slides.pdf
This Handout: . . . /~pulkit/ISIT09Handout.pdf
Further discussion and references can be found in the paper.

1 Decoding energy is significant at small distances

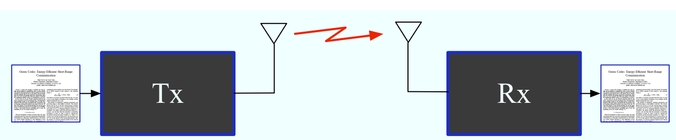


For two sample cases, the required power for distance plot is shown on the left. Notice that required transmit power can be quite small! This is the case because the kT noise at the receiver is also extremely small.

Significantly, the decoding power can be comparable (or even exceed!) the transmit power at small distances. Shown is a state-of-the-art LDPC decoder implementation [Zhang et al '09] where power consumption at high throughputs is 144 mW. At distances of 3 meters or smaller, this exceeds the transmit power for even the high transmit-power 60 GHz systems. For the 3 GHz example here, decoding power is larger than transmit power for a distance as large as 80 meters!

The numbers used for 60 GHz band are: $f = 60$ GHz, temperature $T = 300$K, path-loss exponent $= 3$, Receiver noise figure $= 5$ dB (typical), bandwidth $= 1$ GHz, rate$= 1$ bit/channel use. For 3 GHz band, $f = 3$ GHz, temperature $T = 300$K, path-loss exponent$= 3$, Receiver noise figure $= 20$ dB, bandwidth $= 20$ MHz, rate$= 1$ bit/channel use.

1.1 The 'black-box' model

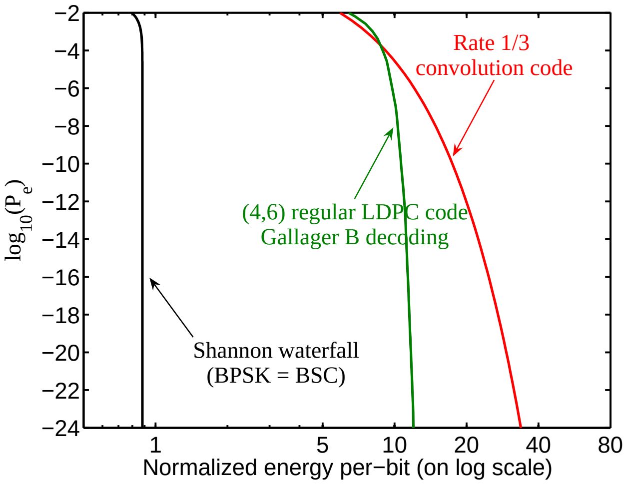


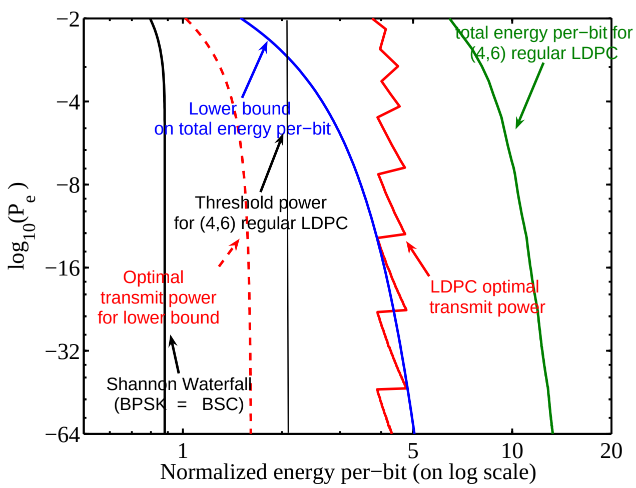
Of relevance is the work by [Massaad, Medard and Zheng'04] on the black-box model where the energy consumed per unit time at the transmitter and receiver is a constant, independent of the error probability and the proximity to capacity. They show it is good to use bursty transmissions that allow Tx and Rx to stay 'off' longer.

The work has been extended to parallel channels and MAC in [Massaad, Zheng and Medard'08]. Processing energy at the relay is considered, for example, by [Prabhakaran and Kumar'09].

2 A finer model for decoding energy

2.1 LDPCs are order optimal from total energy perspective





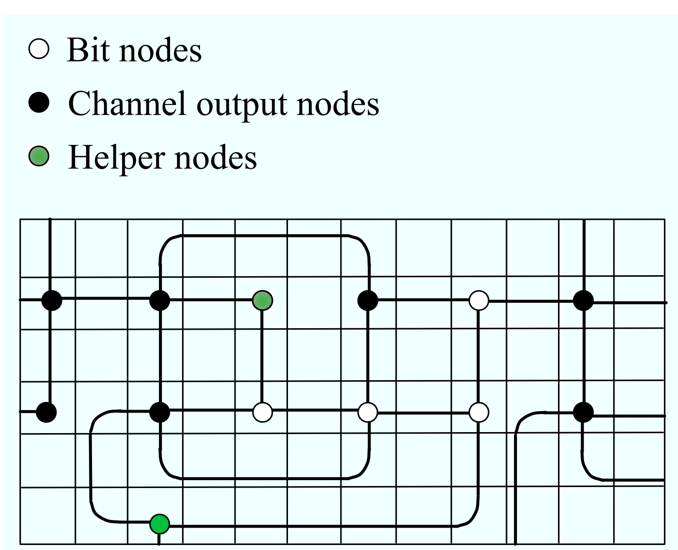
Decoding energy could potentially depend on the desired rate, the transmit power, and the target error probability. To understand this dependence, we assume that each decoder operation requires a constant E joules of energy. The figure shows the total energy per-bit and the optimal transmit energy for convolutional codes (using Viterbi decoding). LDPC codes (even under Gallager B decoding) beat these codes by quite a margin at low error probabilities.

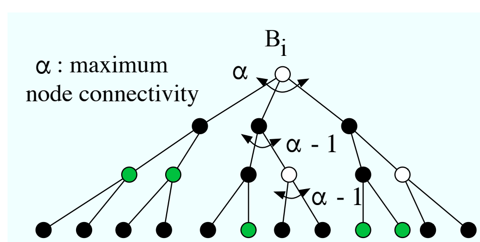
The plots are obtained by using error-exponent analysis for convolutional codes [Viterbi'67], and density-evolution for LDPC codes. We assume that each multiply-accumulate operation for decoding the convolution code, and each node in each iteration of the LDPC decoder, requires 1 pico-Joule of energy. The other parameters are : distance between Tx and Rx = 17 m, carrier frequency = 3 GHz, path-loss exponent = 3, $T = 300$ K, and rate = 1/3 bits/channel-use.

The lower curve also shows the optimal transmit power for (4, 6) LDPC code *which minimizes the total energy per-bit*. The optimal transmit power is bounded away from the threshold for the LDPC code (under the Gallager B decoding algorithm, this corresponds to an SNR of 2.09, a crossover probability of 0.074), showing that the transmitter transmits at a larger power to reduce the decoding energy.

In fact, since on the log-scale the difference between the LDPC performance and the lower bound (see below) is constant at low P_e, regular LDPC codes are order optimal in the total energy consumption sense!

2.2 Lower bounds on complexity of message-passing decoding





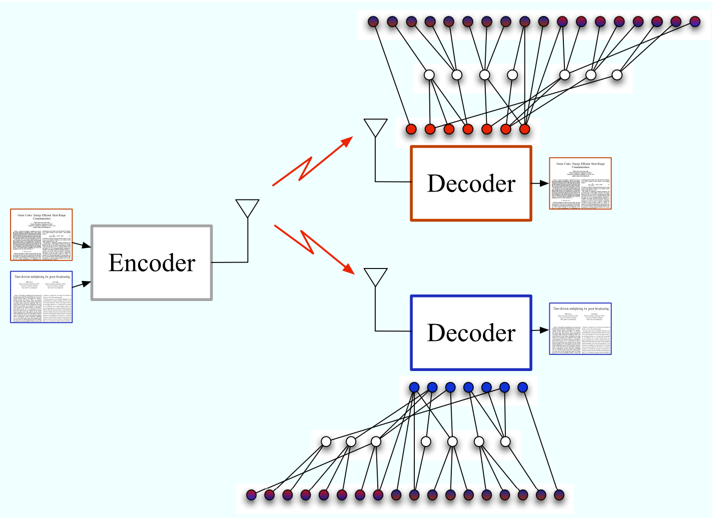
A lower bound on number of decoding iterations for message passing decoding [Sahai, Grover '07]

$$l \gtrsim \frac{1}{\log(\alpha - 1)} \log\left(\frac{\log\frac{1}{P_e}}{(C(P_T) - R)^2}\right),$$

based on deriving error exponents for bit-error probability with respect to neighborhood sizes.

If P_T is small, so that $C(P_T)$ is close to R, then decoding energy blows up. Thus there is a fundamental tradeoff between transmit and decoding energy.

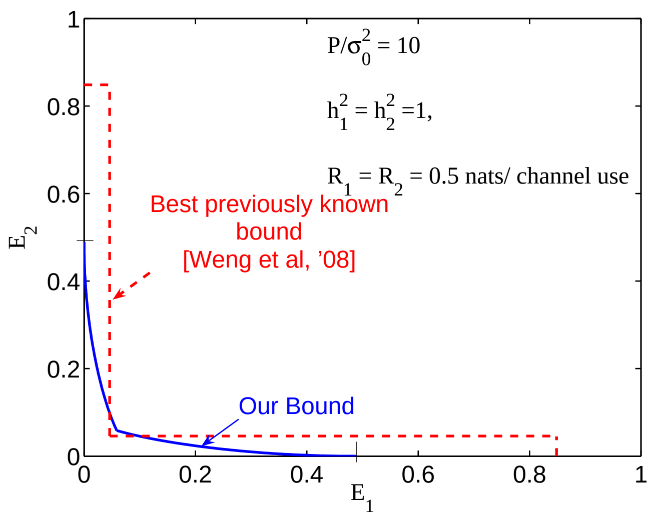
3 Green broadcasting



For a joint scheme (e.g. superposition, dirty-paper coding) *each decoder requires all the output nodes to decode its message*, and hence is potentially decoding energy intensive.

In superposition or dirty-paper coding, a user is forced to decode a part of the message of the other user as well. We ignore this added complexity because we do not know how to account for it. Thus the joint schemes would perform even worse in comparison with time-division multiplexing than what we suggest here.

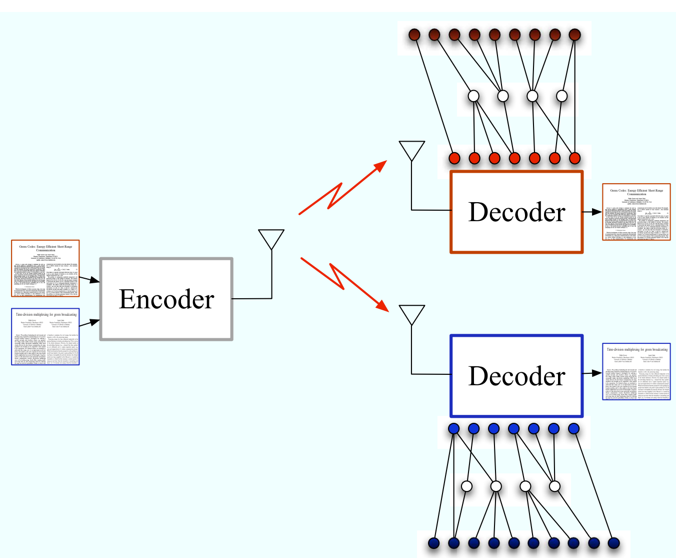
3.1 Outer bounds on the error-exponents for Gaussian broadcast

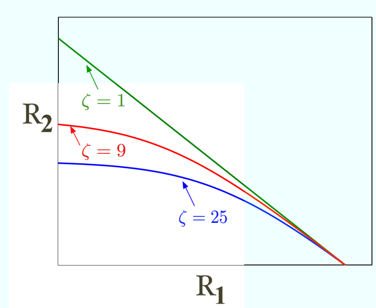


We improve on the best known outer bounds on error exponents for Gaussian broadcast [Weng, Pradhan and Anastasopoulos '08], and extend them to neighborhood sizes and bit-error probability instead of blocklengths and block-error probability. This gives us lower bounds on complexity for any scheme.

The improvement on the outer bound, and extending it to neighborhood sizes and bit-error probability instead of blocklength and block-error probability is the main technical contribution of the paper.

3.2 TDM: Paying transmit power to save per-bit decoding energy

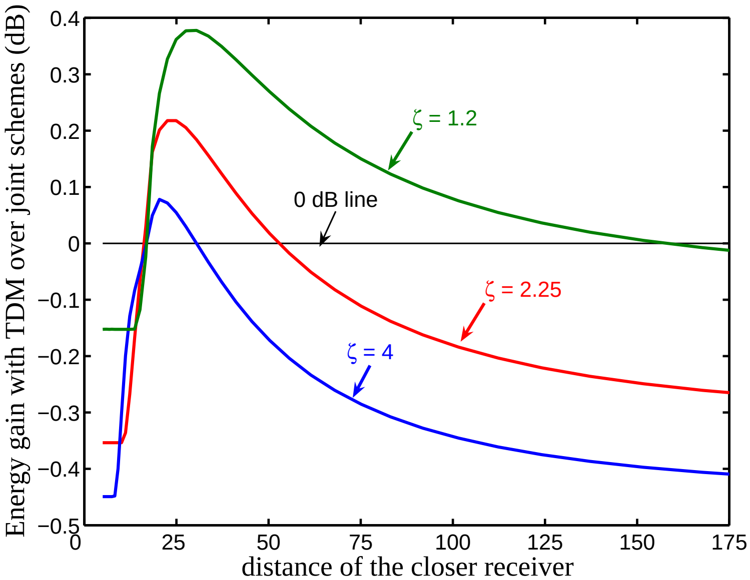




Rate region for Gaussian broadcast : Time-sharing (TDM) achieves close to optimal rates at small ζ

TDM requires larger transmit power to attain the same rates. Specially when the ratio of the distances of the two receivers $\frac{r_2}{r_1} = \sqrt{\zeta}$ is large. However, since each decoder needs only the channel output nodes that encode its own message, *TDM can save on decoding energy.*

3.3 TDM outperforms joint strategies at small distances and small ζ



The TDM performance is evaluated by using bounds on complexity for the point to point case. For joint schemes, the new bounds on error exponents for Gaussian broadcast are used.

The gain can be substantial at small distances and small distance ratios. Thus, at some level, our finer model of decoding energy affirms the conclusions of [Massaad, Zheng, Medard '08] that TDM can outperform transmit-energy-optimal schemes when decoding energy is taken into account.

The figure is plotted using a frequency of 3 GHz, temperature $T = 300$ K, path-loss exponent 2, rate $= \frac{1}{3}$ bits per channel use and a (noise + fading) figure of 30 dB.

4 Summary

This talk intends to bring out the following ideas:

- Wireless communication has entered a short-distance high-throughput (10's of Gbps) regime. Decoding power for these distances and throughputs is often comparable to the transmit power.
- With decoding energy taken into account, the total (transmit + decoding) energy per-bit increases to infinity as $P_e \to 0$. Further, the lower bound optimizing transmit power is strictly larger than the prediction from the Shannon waterfall.
- For the broadcast channel, at short distances, time-division multiplexing is potentially more energy-efficient than joint schemes even under our finer model of decoding energy.
- A general technique (which is used in our work) to arrive at lower bounds on energy consumption is deriving error exponents with respect to neighborhood sizes and bit-error probability. Imposing more structure on the code and decoding algorithm, tighter bounds can be obtained (e.g. see [Sason'08]). It is important to obtain similar bounds for multiuser channels to understand energy limitations of existing codes.
- Regular-LDPC codes and associated belief-propagation decoding are order optimal (though the gap seems substantial) in the total energy-efficiency sense. Further work (in achievability as well as converse) is needed to calculate how close they get to optimal.
- New codes need to be designed with the design criterion of minimizing total energy at a given rate, rather than merely minimizing transmit energy (which is what capacity approaching codes do). For example, protograph-based asymptotically regular LDPC codes [Lentmaier et al '09] would perform better than the other capacity approaching LDPC codes.