Energy Harvesting Receivers

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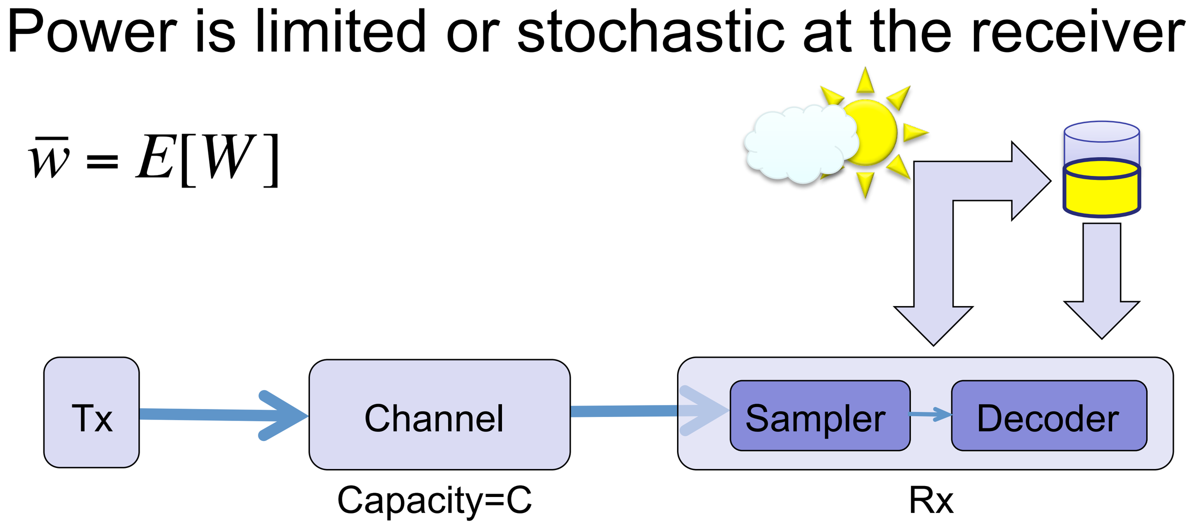
Motivation

- To characterize efficient communication for a receiver with limited source of energy.

System Model

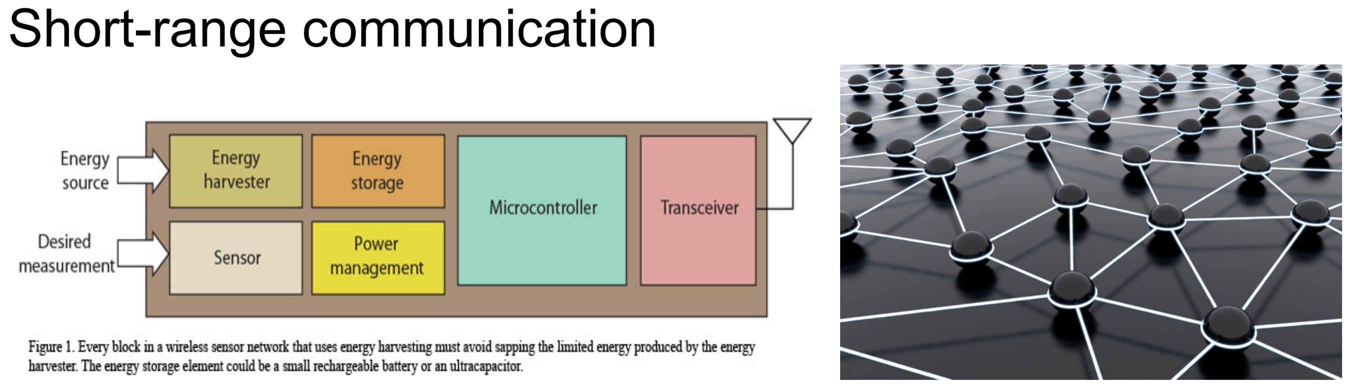
- Power is limited or stochastic at the receiver

$\bar{w} = E[W]$



Applications

- Wireless sensor networks.
- Short-range communication



[Electronicdesign.com]

Power Consumption at the Receiver

$$P_{receiver} = \underbrace{\underbrace{P_{mix} + P_{syn} + P_{LNA} + P_{filter}}_{\text{fixed}} + \underbrace{P_{IFA}}_{\text{small}} + P_{ADC} + P_D}_{P_{sampling}}$$

$$P_{ADC} \approx \frac{3V_{dd}^2 L_{min}(2B + f_{cor})}{10^{-0.1525n_1 + 4.838}} \quad V_{dd} = 3\text{ V},\ L_{min} = 0.5\mu\text{m},\ n_1 = 10,\ fcor = 1\text{ MHz}$$

[Shuguang Cui, A.J. Goldsmith, and A. Bahai 2005]

$$E_{\text{sampling}} \approx \frac{1}{B}\left(\frac{3V_{dd}^2 L_{min}(2B + f_{cor})}{10^{-0.1525n_1 + 4.838}} + 105.8\text{mW}\right)$$

We assume Esampling=1 and every other energy component can be scaled accordingly.

Performance Metric

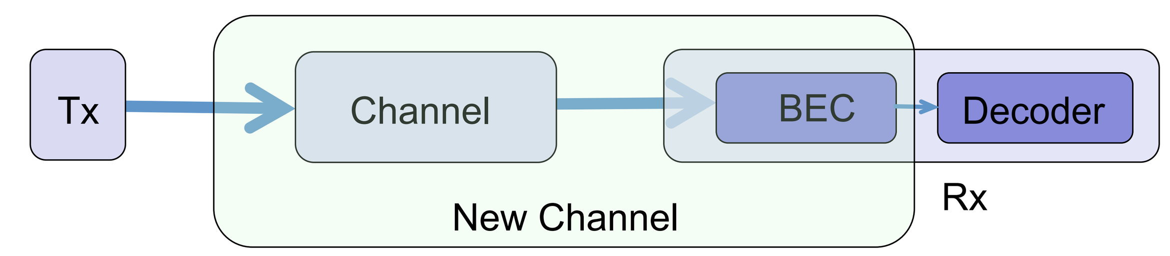
- Reliable Communication Rate: $\rho(t) = \frac{1}{t}\sum_{i=1}^{N(t)} R_i I_i$

$N(t)$ = the number of codewords sent by time t.

R_i = the code rate of packet i.

$I_i = 1$, if the receiver decodes the packet i reliably.

Dropping a Sample: Erasure Channel



- C = capacity of original channel
- λ = sampling rate=1- erasure rate
- ⇨ Cλ = capacity of the new channel

[S. Verdu and T. Weissman, 2008]

- Conjecture: Decoding energy is an increasing function of the code rate R that diverges as R approaches capacity:

$$O((n/\delta)\ln(1/\delta))$$

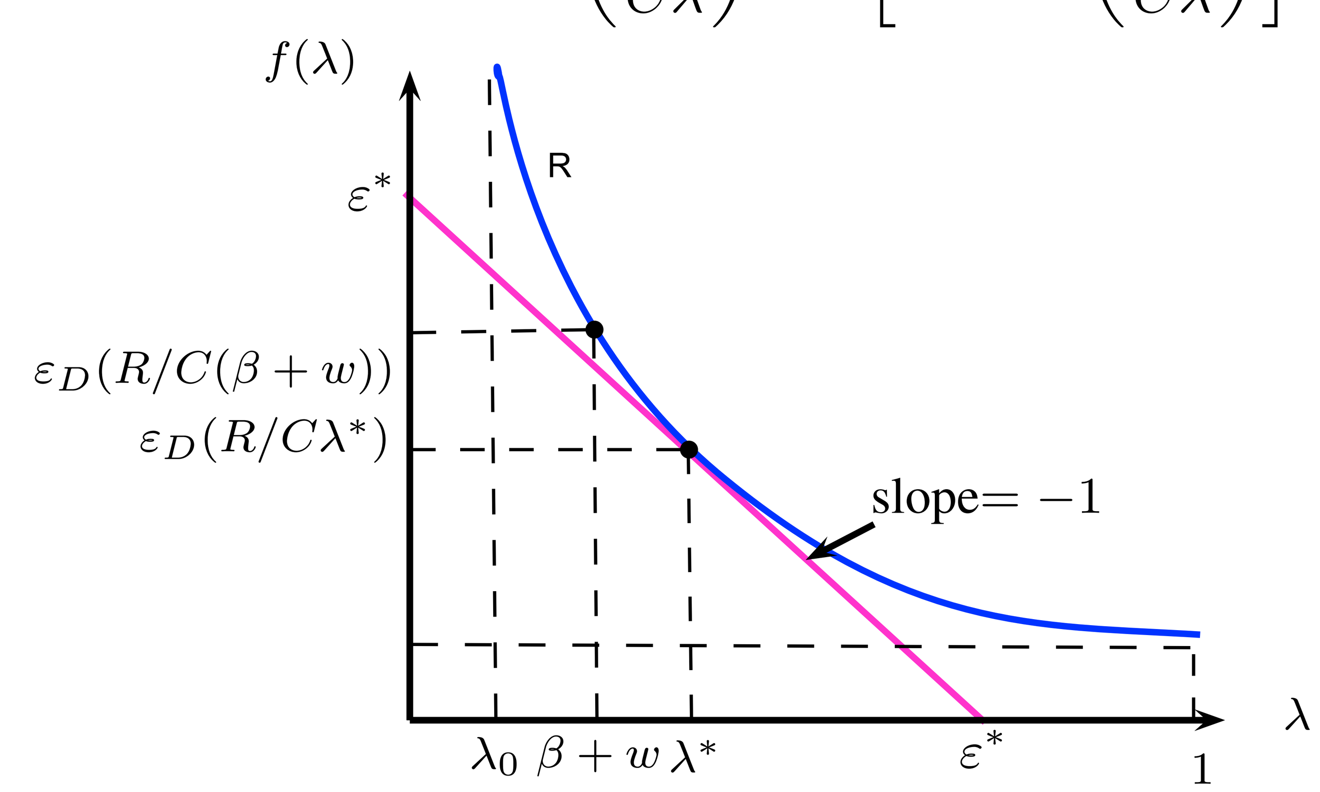
[A. Khandekar and R.J. McEliece, 2001]
[T. Richardson and R. Urbanke, 2003]

The gap to the capacity: $\delta = 1 - R/C\lambda$

Sampling and Decoding Energy Tradeoff

Total Energy Consumption:

$$n\mathcal{E} = s + n\mathcal{E}_D\left(\frac{R}{C\lambda}\right) = n\left[\lambda + \mathcal{E}_D\left(\frac{R}{C\lambda}\right)\right]$$



Minimum energy requirement : (unbounded battery)

$$\mathcal{E}^*(R) = \lambda^*(R) + \mathcal{E}_D\left(\frac{R}{C\lambda^*(R)}\right)$$

Minimum energy requirement : (bounded battery)

$$\tilde{\lambda}(R) = \min\{\lambda^*(R), \beta + \bar{w}\}$$

$$\tilde{\mathcal{E}}(R) = \mathcal{E}_D(R/C\tilde{\lambda}) + \tilde{\lambda}(R)$$

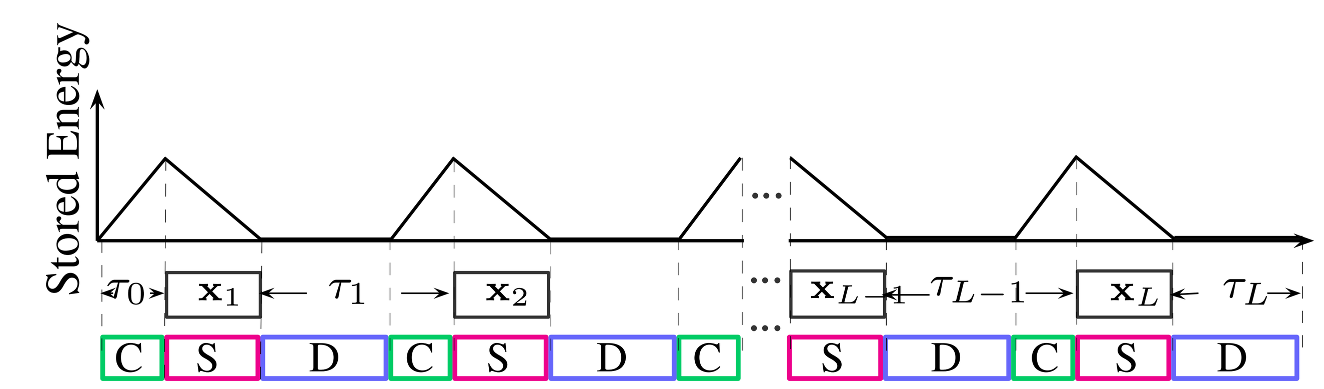
Optimum Communication for a Fixed Code Rate

- **Outerbound:**

It can be shown that for a fixed code rate R: $\rho \le \frac{\bar{w}R}{\bar{\mathcal{E}}(R)}$

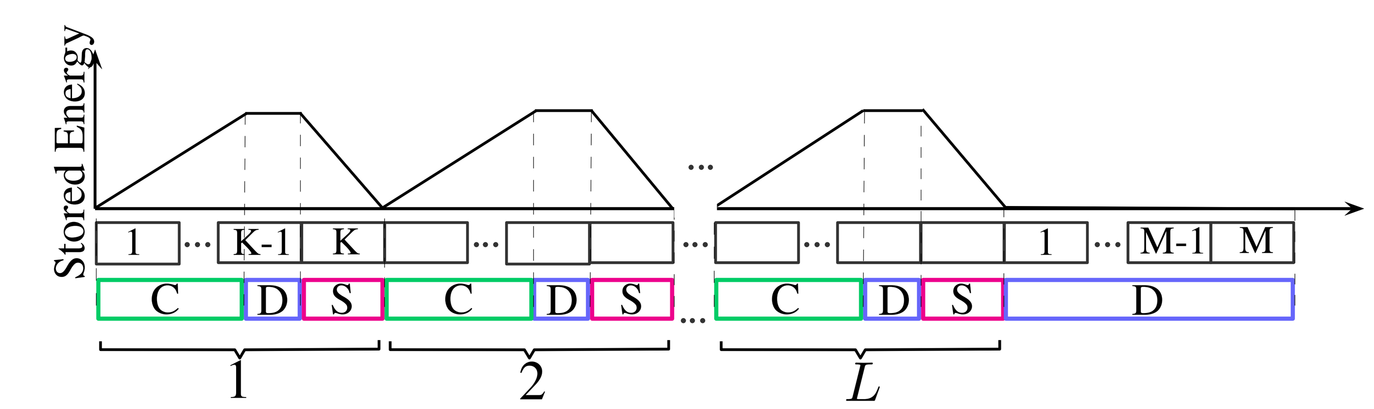
- **Achievability:**

Variable-Timing Transmission: Tx inserts idle periods between codewords to give the Rx time to decode and recharge its battery for sampling the next codeword.



C: **C**ollecting energy S: **S**ampling D: **D**ecoding

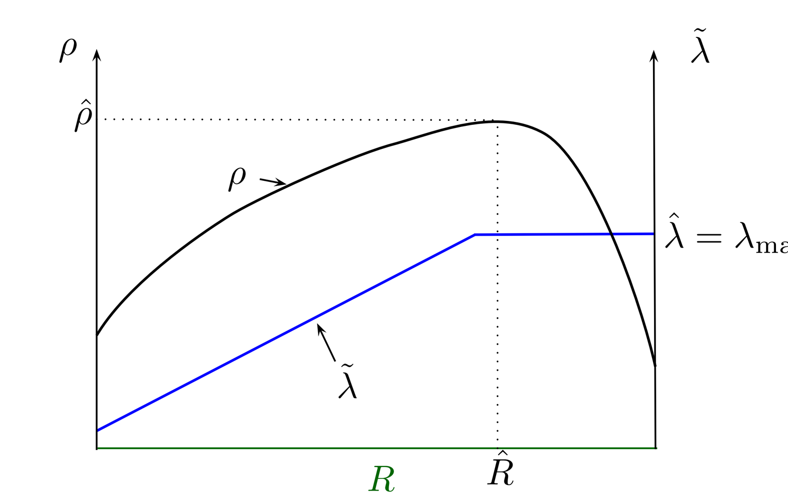
Fixed-Timing Transmission: Tx sends codewords without idle periods between transmissions. Rx may drop some packets to collect energy or do decoding.



Code Rate Optimization

$$\hat{\rho} = \max_{R,\lambda} \frac{\bar{w}R}{\mathcal{E}(R)}$$
$$\text{s.t.}\quad 0 < R < C\lambda$$
$$\lambda \le \lambda_{\max}.$$

$$\lambda_{\max} \triangleq \min\{\beta + \bar{w}, 1\}$$



$$\hat{\lambda} = \lambda_{\max} \qquad \hat{\rho} = \frac{\bar{w}C\lambda_{\max}}{\mathcal{E}'_D(\hat{R}/C\lambda_{\max})}$$

Summary

- At low code rates, the receiver has tradeoff between sampling and decoding
- Sampling energy, even if it is small, may limit the communication rate.
- Fixed-timing transmission may not achieve the energy constraint outerbound.

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