Design Principles for Energy Harvesting Wireless Communication Networks

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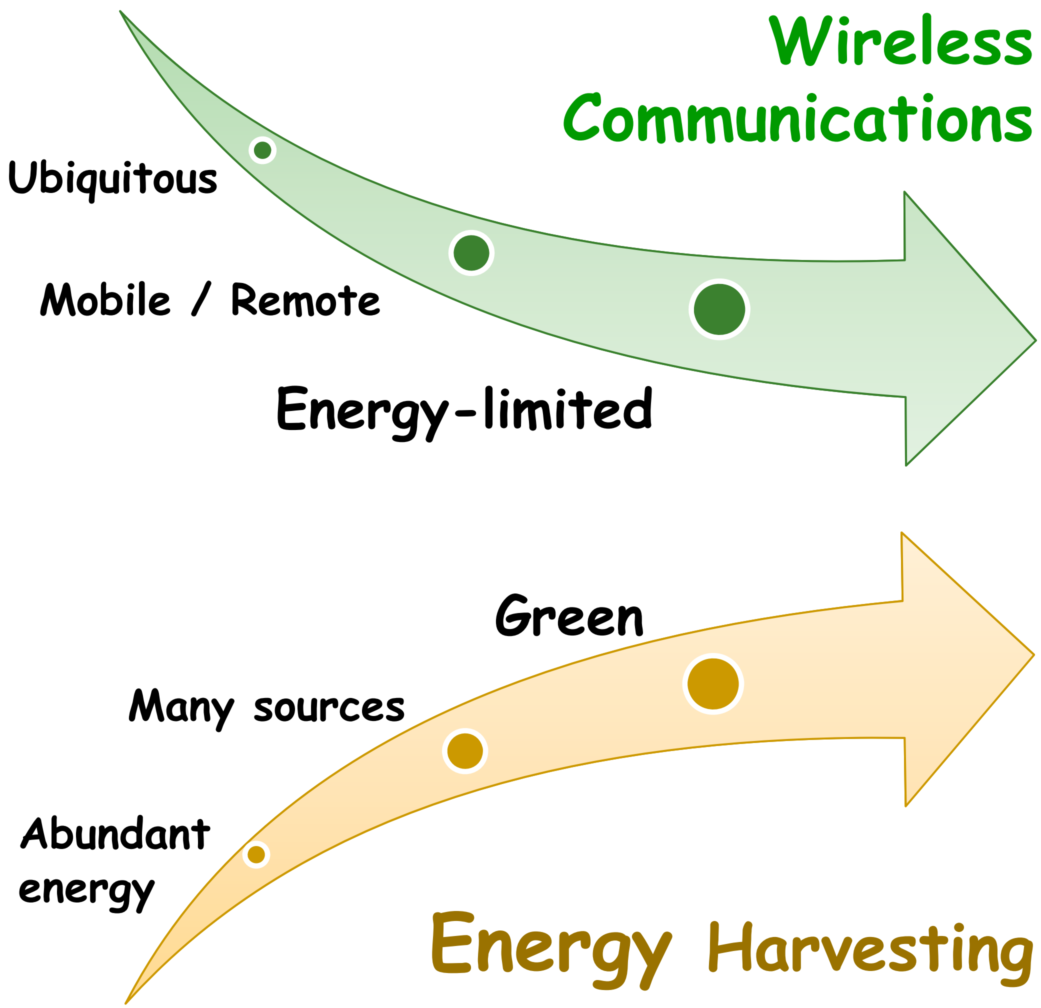
Acknowledgment: NSF 0964364

Introduction



Energy
Harvesting
Wireless
Networks

Energy Harvesting Networks

- **Wireless networking with rechargeable (energy harvesting) nodes:**
  - Green, self-sufficient nodes,
  - Extended network lifetime,
  - Smaller nodes with smaller batteries.

A relatively new field with increasing interest.

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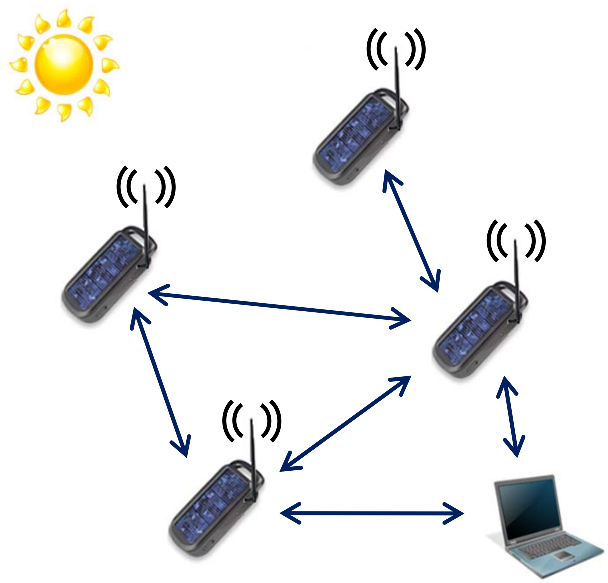
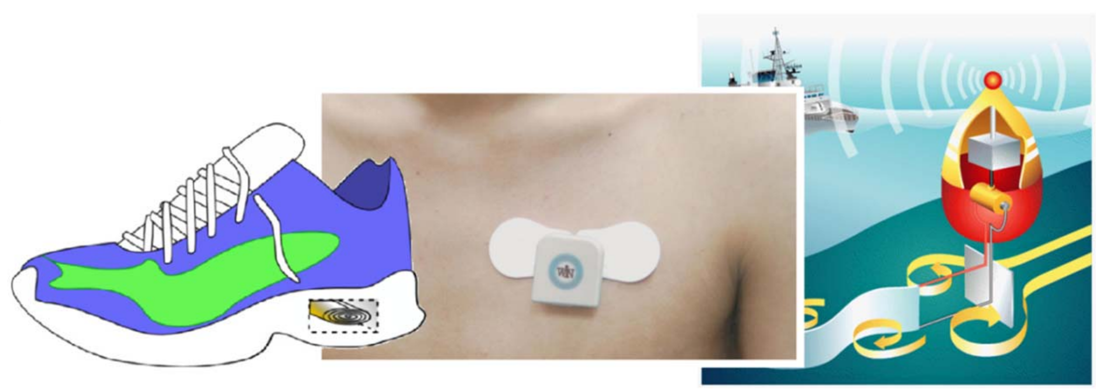
Some Applications

Wireless sensor networks

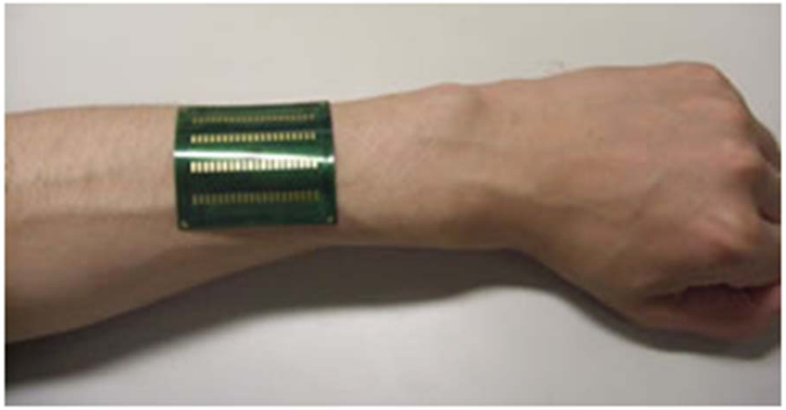


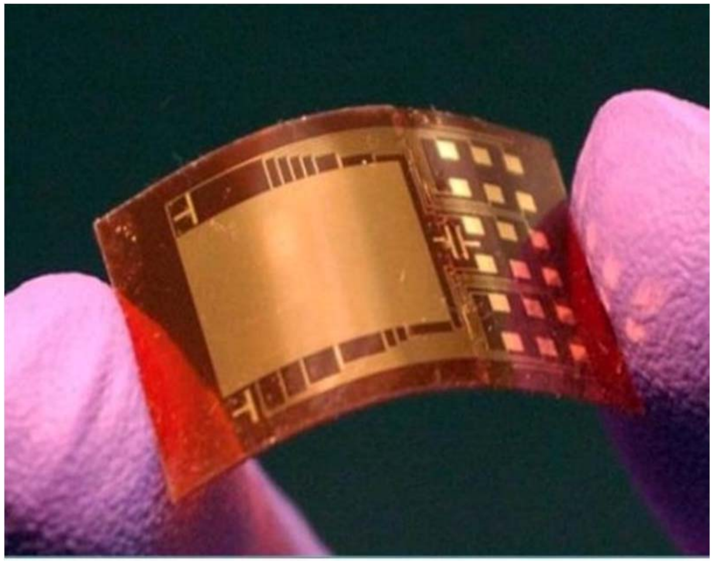
Green
communications



Harvesting Energy

- Fujitsu's hybrid device utilizing **heat or light.**





- Nanogenerators built at Georgia Tech, utilizing **strain**

Image Credits: (top) http://www.fujitsu.com/global/news/pr/archives/month/2010/20101209-01.html
(bottom) http://www.zeitnews.org/nanotechnology/squeeze-power-first-practical-nanogenerator-developed.html

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New Network Design Challenge

- A **set of energy feasibility constraints** based on energy harvests govern the communication resources.
- **Main design question:**

When and at what rate/power should a rechargeable (energy harvesting) node transmit?

- **Optimality?** **Throughput; Delivery Delay**
- **Outcome: Optimal Transmission Schedules**

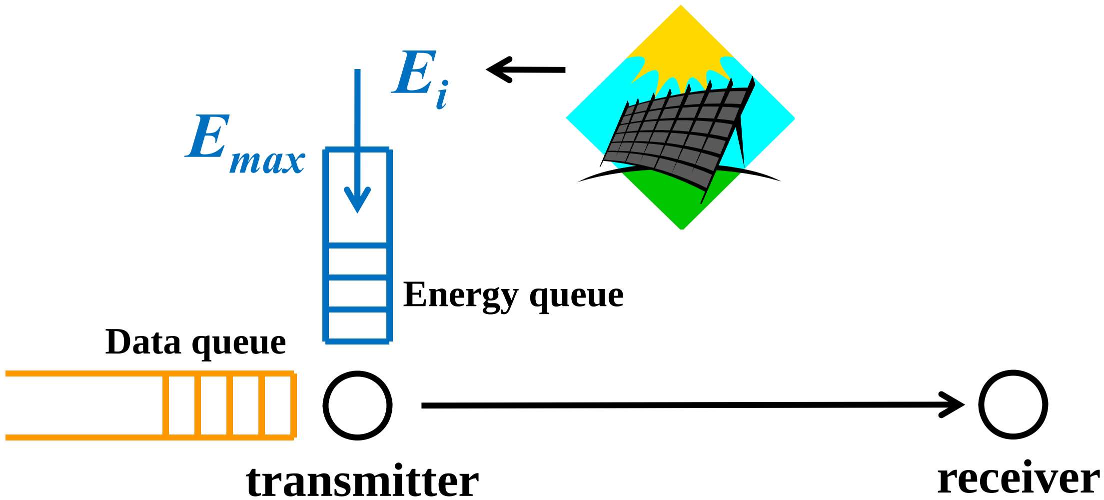
Throughput Maximization

[Tutuncuoglu-Y.'12]

- One Energy harvesting transmitter.
- Find optimal power allocation/transmission policy that departs maximum number of bits in a given duration **T**.
- Energy available intermittently.
- Up to a certain amount of energy can be stored by the transmitter → **BATTERY CAPACITY**.

System Model

- Energy harvesting transmitter:



- Energy **arrives intermittently** from harvester
- Transmitter has **backlogged data** to send within a deadline T.
- Stored in a **finite battery** of capacity E_{max}

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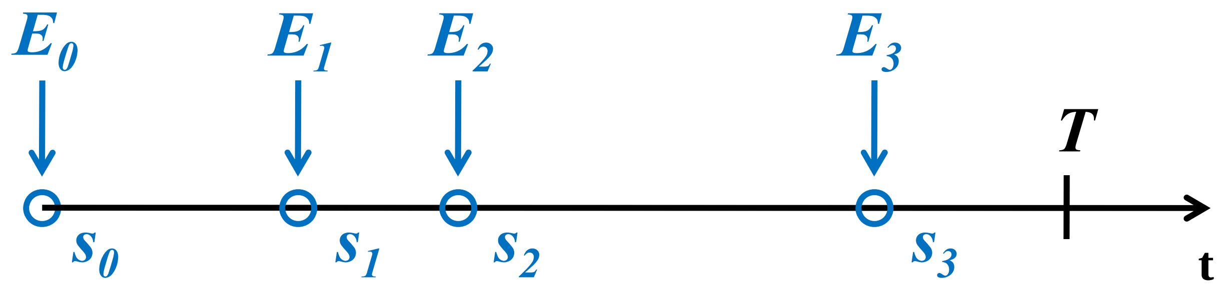
System Model

- Energy arrivals of energy E_i at times s_i



- Arrivals known **non-causally** by transmitter,
- Design parameter: **power** $\rightarrow$ **rate** $r(p)$.

Notations and Assumptions

- Power allocation function: $p(t)$
- Energy consumed: $\int_0^T p(t)dt$
- Transmission with power p yields a rate of $r(p)$
- Short-term throughput: $\int_0^T r(p(t))dt$

Power-Rate Function

- Transmission with power p yields a rate of $r(p)$

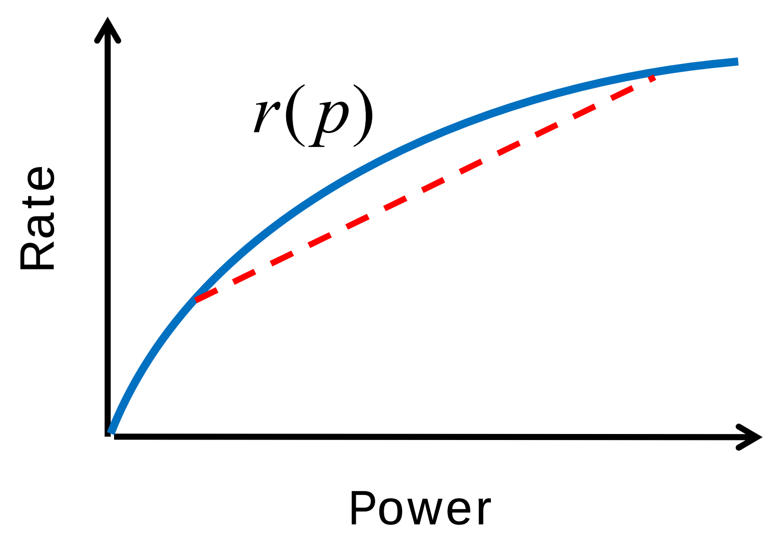
- **Assumptions on r(p):**

  i. $r(0)=0,\ r(p) \to \infty \ as\ p \to \infty$

  ii. increases monotonically in p

  iii. strictly concave

  iv. $r(p)$ continuously differentiable

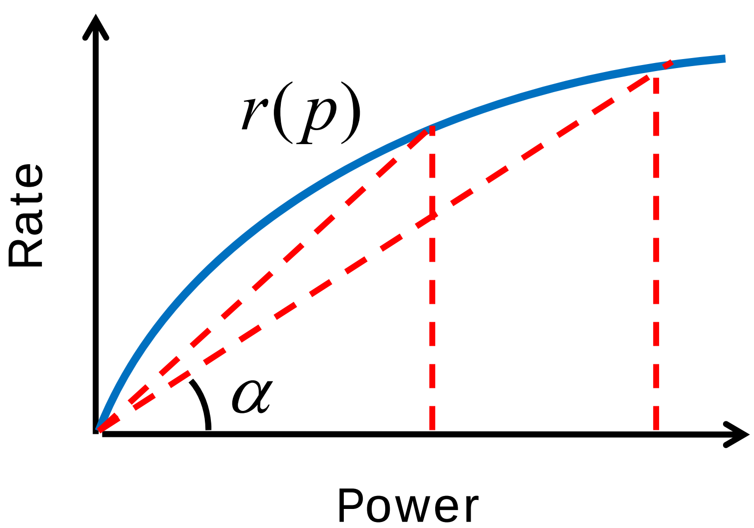


Example: AWGN Channel, $r(p) = \frac{1}{2}\log\left(1+\frac{p}{N}\right)$

Power-Rate Function

- $r(p)$ strictly concave, increasing, $r(0)=0$ implies

$$\tan(\alpha) = \frac{r(p)}{p} \text{ is monotonically decreasing in } p$$



- Given a fixed energy, a longer transmission with lower power departs more bits.

Lazy Scheduling, El Gamal 2001

- Also, $r^{-1}(p)$ exists and is strictly convex

Energy Constraints

(Energy arrivals of E_i at times s_i)

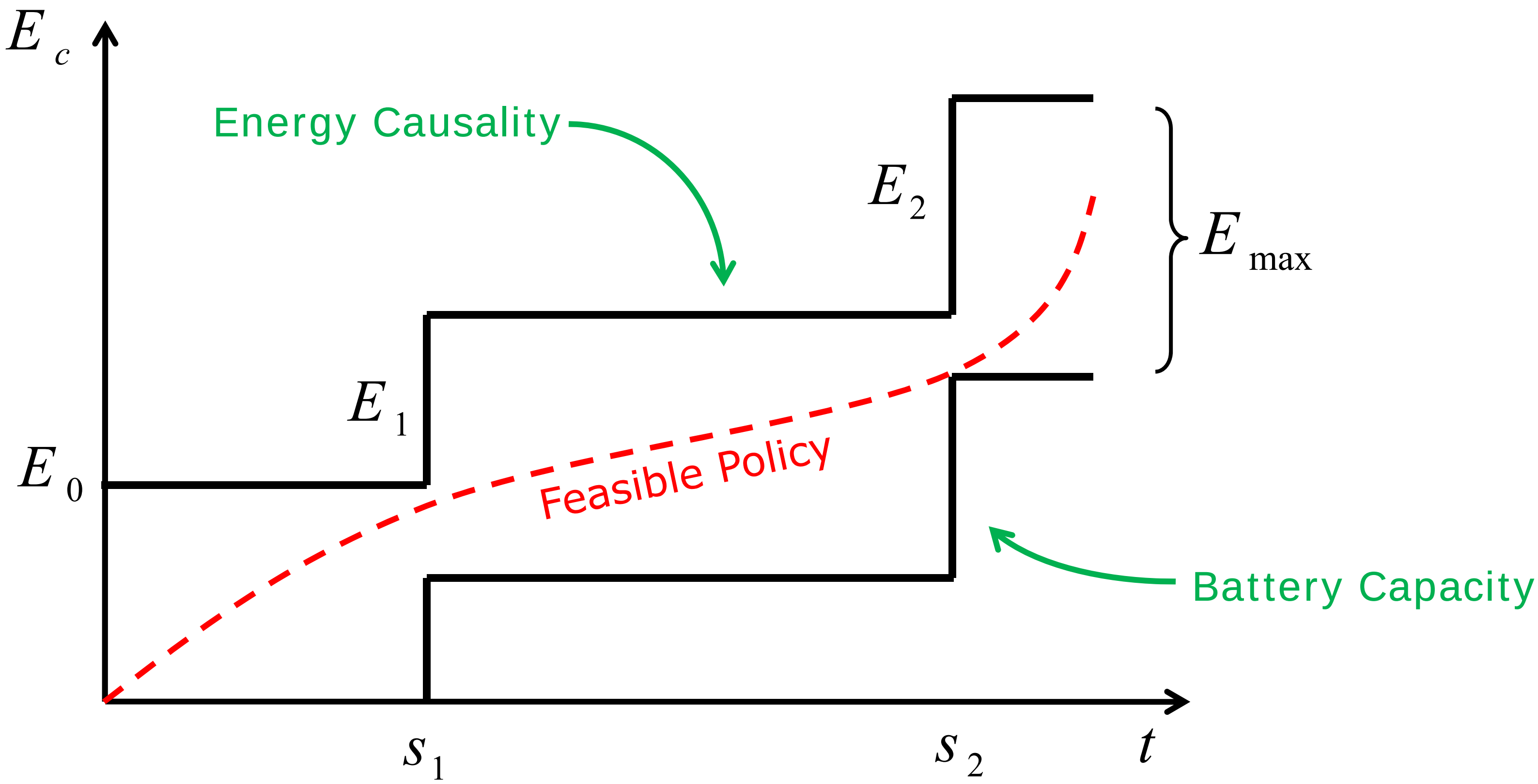
- **Energy Causality:** $\sum_{i=0}^{n-1} E_i - \int_0^{t'} p(t)dt \geq 0 \qquad s_{n-1} \leq t' \leq s_n$

- **Battery Capacity:** $\sum_{i=0}^{n-1} E_i - \int_0^{t'} p(t)dt \leq E_{\max} \qquad s_{n-1} \leq t' \leq s_n$

- **Set of energy-feasible power allocations**

$$\mathfrak{P} = \left\{ p(t) \,\middle|\, 0 \leq \sum_{i=0}^{n-1} E_i - \int_0^{t'} p(t)dt \leq E_{\max}, \forall n > 0, s_{n-1} \leq t' \leq s_n \right\}$$

Energy “Tunnel”



Optimization Problem

- Maximize total number of transmitted bits by deadline **T**

$$\max_{p(t)} \int_0^T r(p(t))dt, \qquad s.t. \quad p(t) \in \mathfrak{P}$$

$$\mathfrak{P} = \left\{ p(t) \,\middle|\, 0 \le \sum_{i=0}^{n-1} E_i - \int_0^{t'} p(t)dt \le E_{\max}, \forall n > 0, s_{n-1} \le t' \le s_n \right\}$$

- Convex constraint set, concave maximization problem

Necessary conditions for optimality of a transmission policy

- **Property 1:** **Transmission power remains constant between energy arrivals.**

- **Proof: By contradiction**

Let $p(t_1) > p(t_2)$ for some $t_1, t_2 \in [0, \Gamma]$ with given total energy

Define $p^*(t) = \begin{cases} p(t_1) - \varepsilon & [t_1 - \delta, t_1 + \delta] \\ p(t_2) + \varepsilon & [t_2 - \delta, t_2 + \delta] \\ p(t) & else \end{cases}$

Then $\int_0^\Gamma r(p^*(t))\, dt > \int_0^\Gamma r(p(t))\, dt$ due to strict concavity of $r(p)$

Necessary conditions for optimality

Let the total consumed energy in epoch $[s_i, s_{i+1}]$ be E_{total}

which is available in energy queue at $t = s_i$

Then a constant power transmission

$$p' = \frac{E_{total}}{s_{i+1} - s_i}, \qquad t \in [s_i, s_{i+1}]$$

is feasible and strictly better than a non-constant transmission.

Transmission power can change only at s_i

Necessary conditions for optimality

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- **Property 2:** Battery never overflows.

Proof:

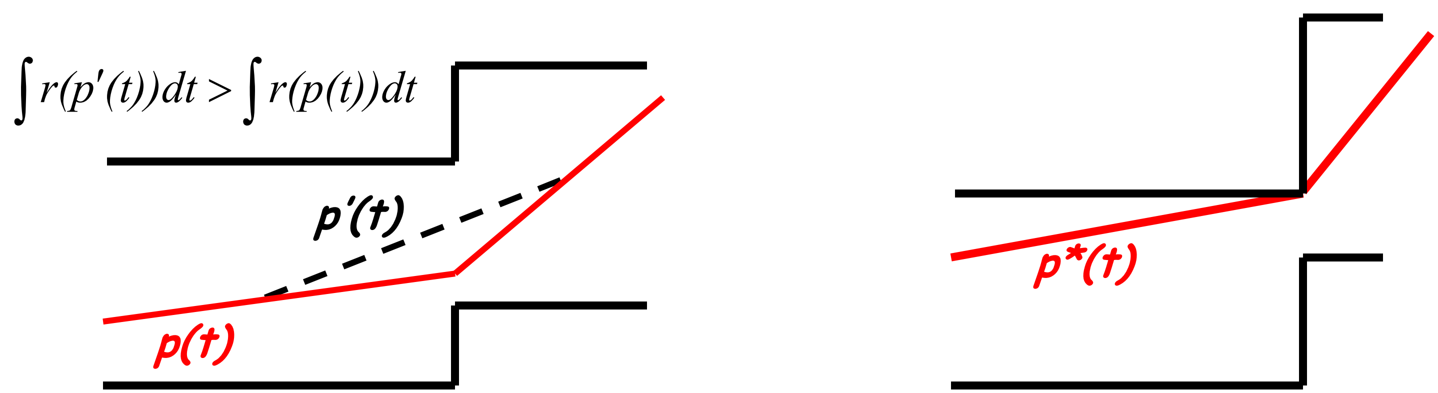
Assume an energy of Δ overflows at time τ

Define $p'(t) = \begin{cases} p(t) + \dfrac{\Delta}{\delta} & [\tau - \delta, \tau] \\ p(t) & else \end{cases}$

Then $\int_0^T r(p'(t))dt > \int_0^T r(p(t))dt$ since $r(p)$ is increasing in p

Necessary conditions for optimality of a transmission policy

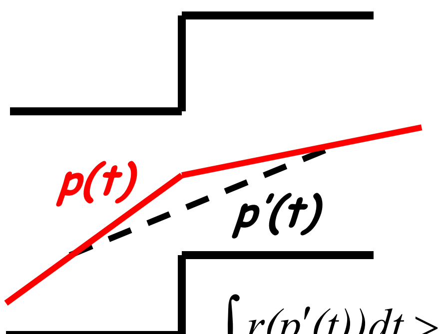
- **Property 3:** Power level increases at an energy arrival instant only if battery is depleted. Conversely, power level decreases at an energy arrival instant only if battery is full.



Policy can be improved **Policy cannot be improved**

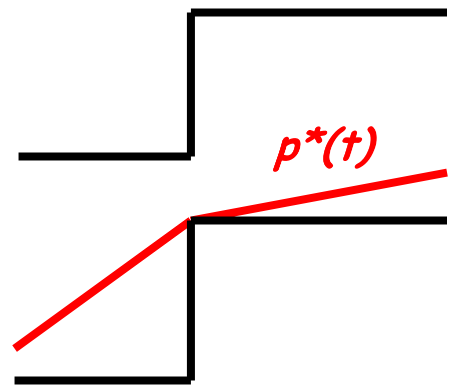
Necessary conditions for optimality of a transmission policy

- **Property 3:** Power level increases at an energy arrival instant only if battery is depleted. <u>Conversely, power level decreases at an energy arrival instant only if battery is full.</u>



$$\int r(p'(t))dt > \int r(p(t))dt$$

Policy can be improved



Policy cannot be improved

Necessary conditions for optimality of a transmission policy

- **Property 4:** Battery is depleted at the end of transmission.

Proof: Assume an energy of Δ remains after p(t)

Define $$p'(t) = \begin{cases} p(t) + \dfrac{\Delta}{\delta} & [T-\delta, T] \\ p(t) & else \end{cases}$$

Then $\int_0^T r(p'(t))dt > \int_0^T r(p(t))\,dt$ since $r(p)$ is increasing

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Necessary Conditions for Optimality

Implications of Properties 1-4:

- **Structure of optimal policy:** (Property 1)

$$p(t) = \begin{cases} p_n & i_{n-1} < t < i_n \\ 0 & t > T \end{cases}, \qquad i_n \in \{s_n\}, \quad p_n \text{ constant}$$

- For power to increase or decrease, policy must meet the upper or lower boundary of the tunnel respectively (Property 3)
- At termination step, battery is depleted (Property 4).
- An algorithmic solution can be found recursively, see [Tutuncuoglu-Y.12]

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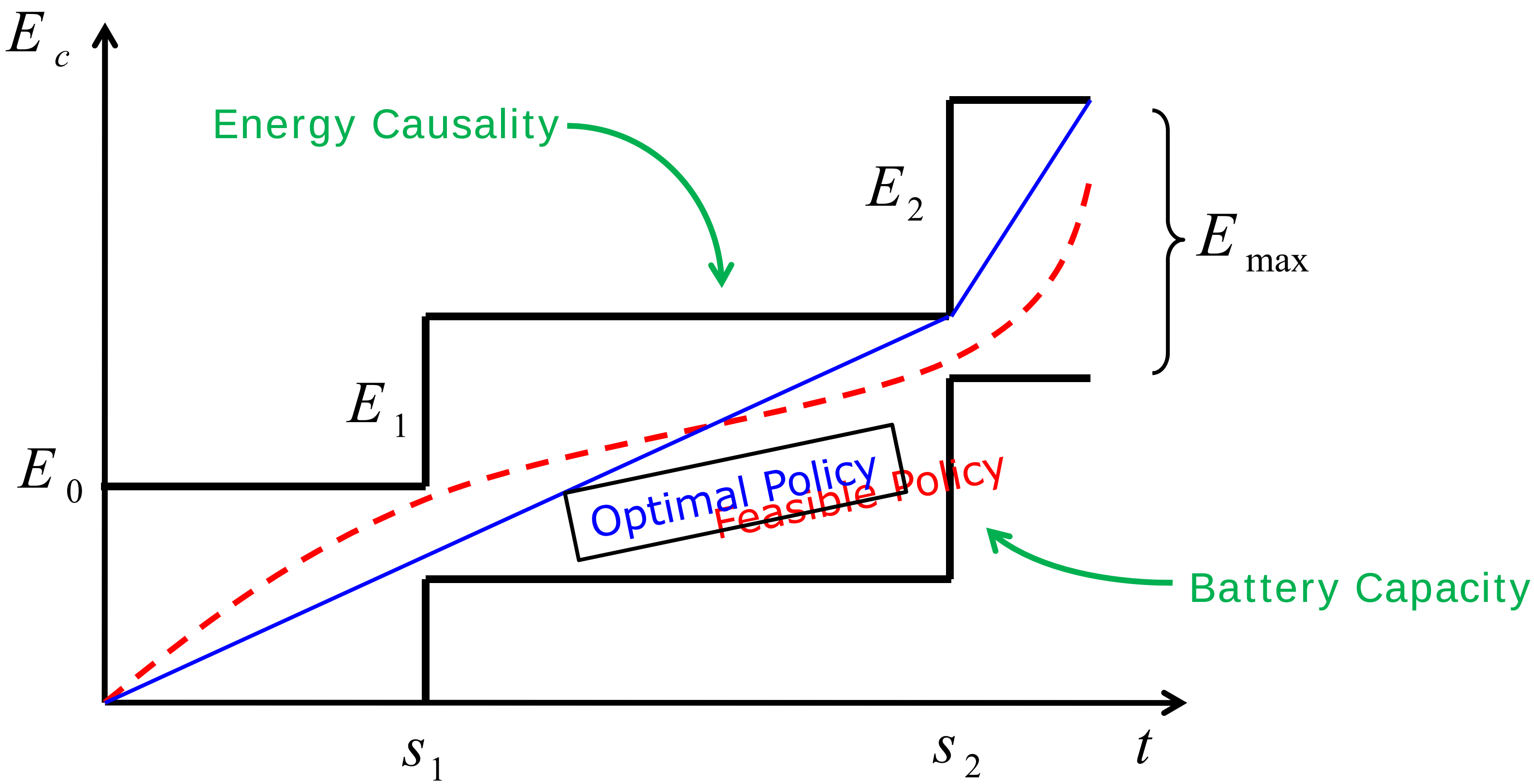
Energy "Tunnel"



Shortest Path Interpretation

- **Optimal policy is identical for any concave power-rate function!**
- Let $r(p) = -\sqrt{p^2+1}$, then the problem solved becomes:

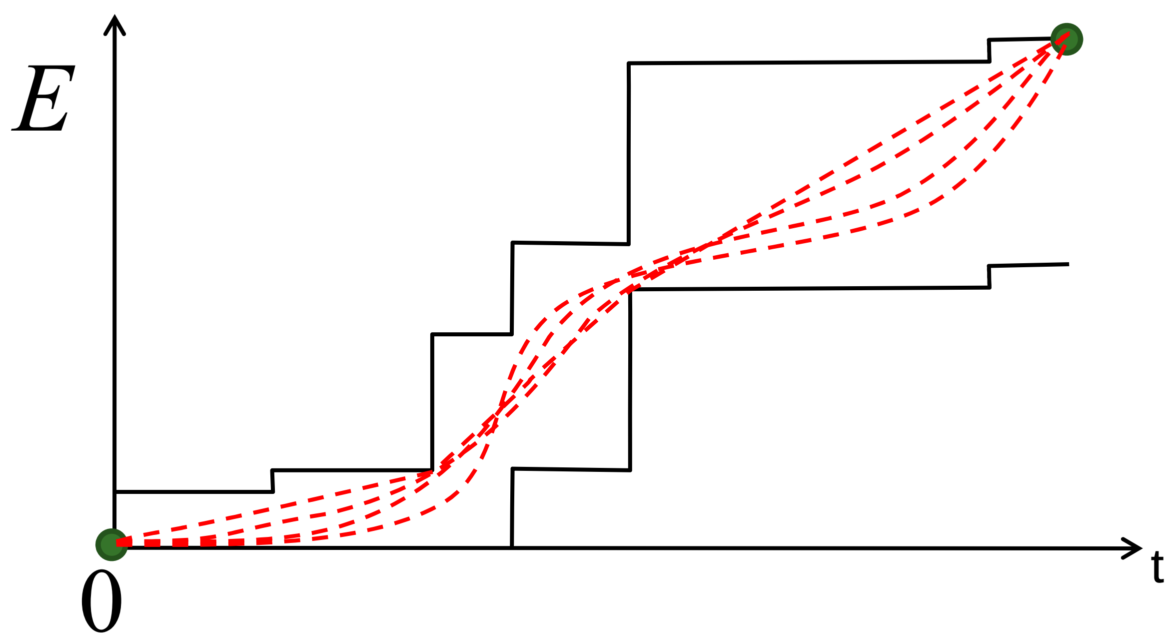
$$\max_{p(t)} \int_0^T -\sqrt{p^2(t)+1}\, dt \qquad s.t. \;\; p(t) \in \mathfrak{P}$$

$$= \min_{p(t)} \underbrace{\int_0^T \sqrt{p^2(t)+1}\, dt}_{\text{length of policy path in energy tunnel}} \qquad s.t. \;\; p(t) \in \mathfrak{P}$$

$\Rightarrow$ The **throughput maximizing policy** yields the **shortest path** through the energy tunnel for any concave power-rate function.

Shortest Path Interpretation

- **Property 1:** Constant power is better than any other alternative
- **Shortest path** between two points is a line (constant slope)



Alternative Solution (Using Property 1)

- Transmission power is constant within each epoch:

$$p(t) = \{ p_i, t \in epoch \;\; i, \;\; i = 1, \ldots, N \}$$

(N: Number of arrivals within [0,T])

$$\max_{p_i} \sum_{i=1}^{N} L_i . r(p_i)$$

(L_i: length of epoch i)

$$s.t. \quad 0 \le \sum_{i=1}^{n} E_i - L_i p_i \le E_{\max} \qquad n = 1, \ldots, N$$

- KKT conditions → optimum power policy.

Solution

- Complementary Slackness Conditions:

$$\lambda_n\left(\sum_{i=1}^{n} L_i p_i - E_i\right) = 0 \qquad \forall n$$

$$\mu_n\left(\sum_{i=1}^{n} E_i - L_i p_i - E_{\max}\right) = 0 \qquad \forall n$$

λ_n's are positive only when battery is empty $\left(\sum_{i=1}^{n} L_i p_i - E_i\right) = 0$

μ_n's only positive only when battery is full $\left(\sum_{i=1}^{n} E_i - L_i p_i - E_{\max}\right) = 0$

$$p_n^* = \frac{1}{\sum_{j=n}^{N}(\lambda_j - \mu_j)} - 1$$

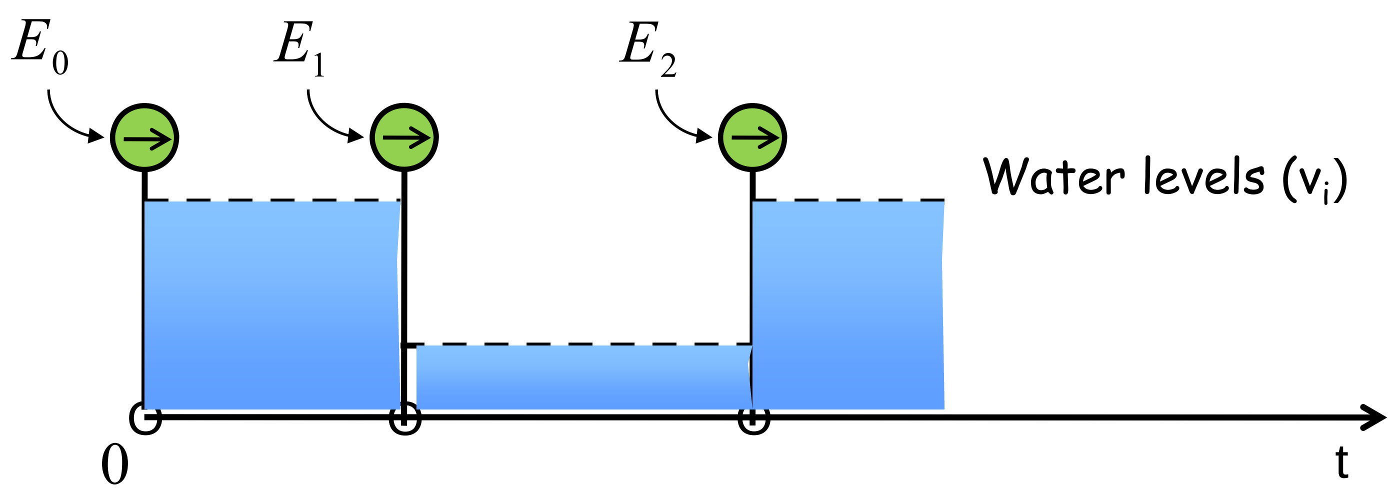
increases at a positive λ_n

decreases at a positive μ_n

(Water Filling-Goldsmith 1994)

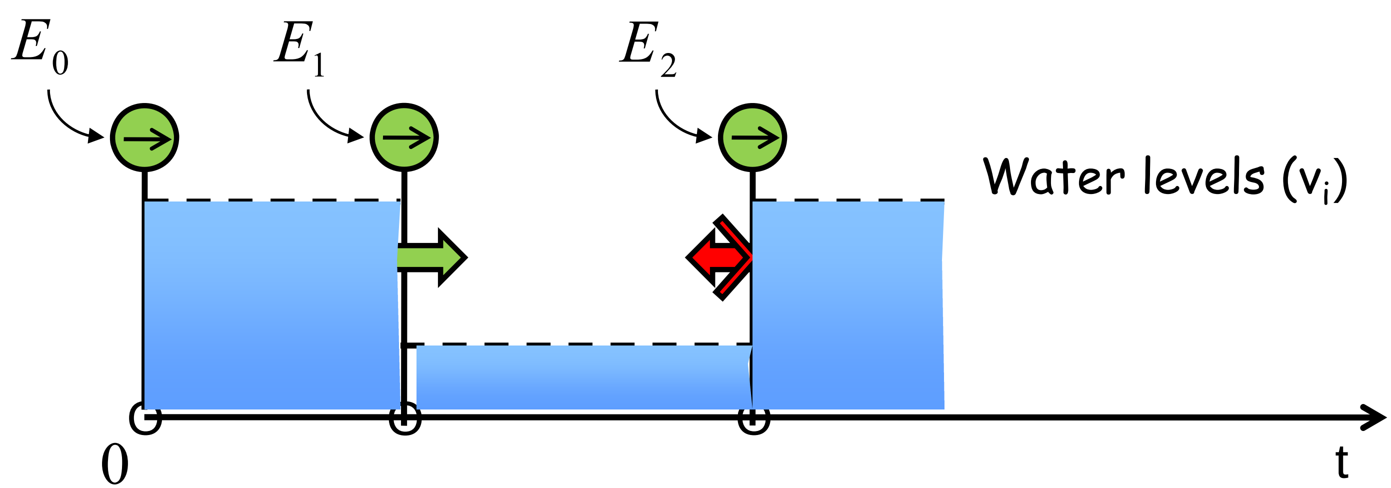
Directional Water-Filling

- [Ozel, Tutuncuoglu, Ulukus, Y., 2011]
- Harvested energies filled into epochs individually



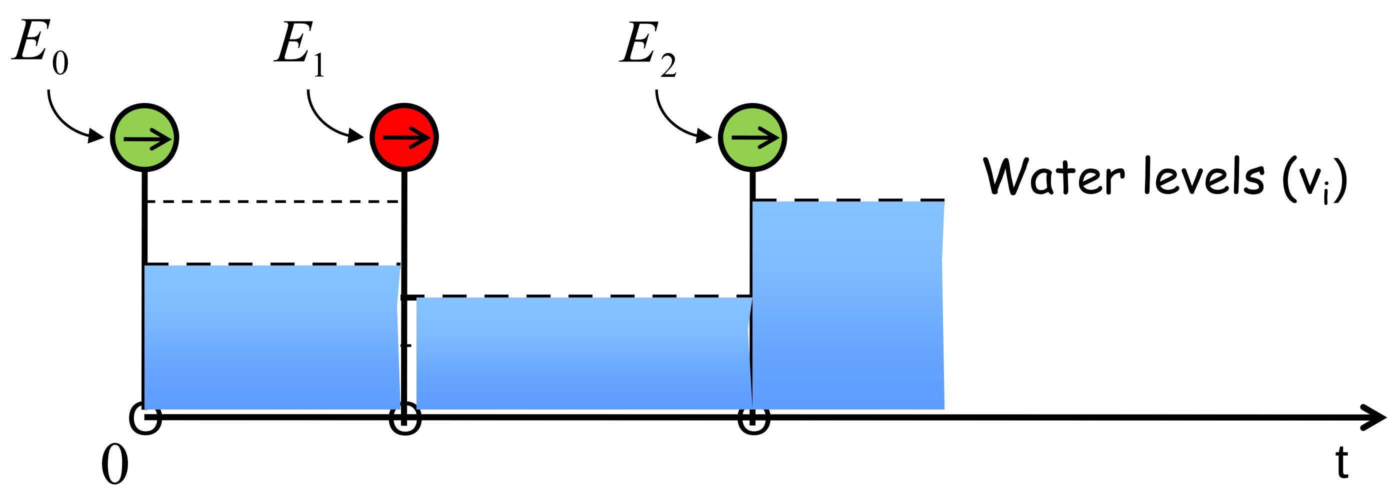
Directional Water-Filling

- Harvested energies filled into epochs individually
- Constraints:
  - **Energy Causality**: water-flow only forward in time



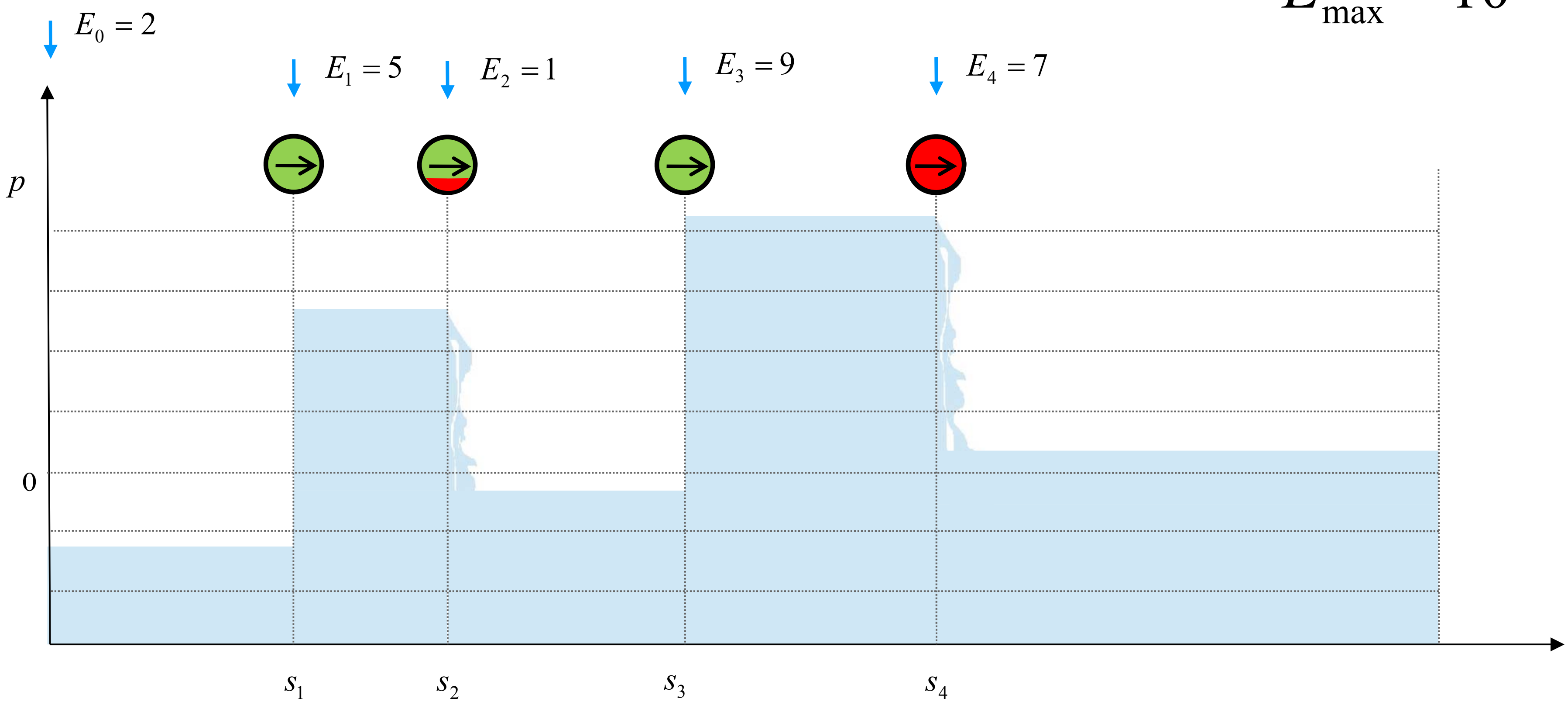
Directional Water-Filling

- Harvested energies filled into epochs individually
- Constraints:
  - **Energy Causality**: water-flow only forward in time
  - **Battery Capacity**: water-flow limited to E_{max} by taps



Example

$E_{\max} = 10$



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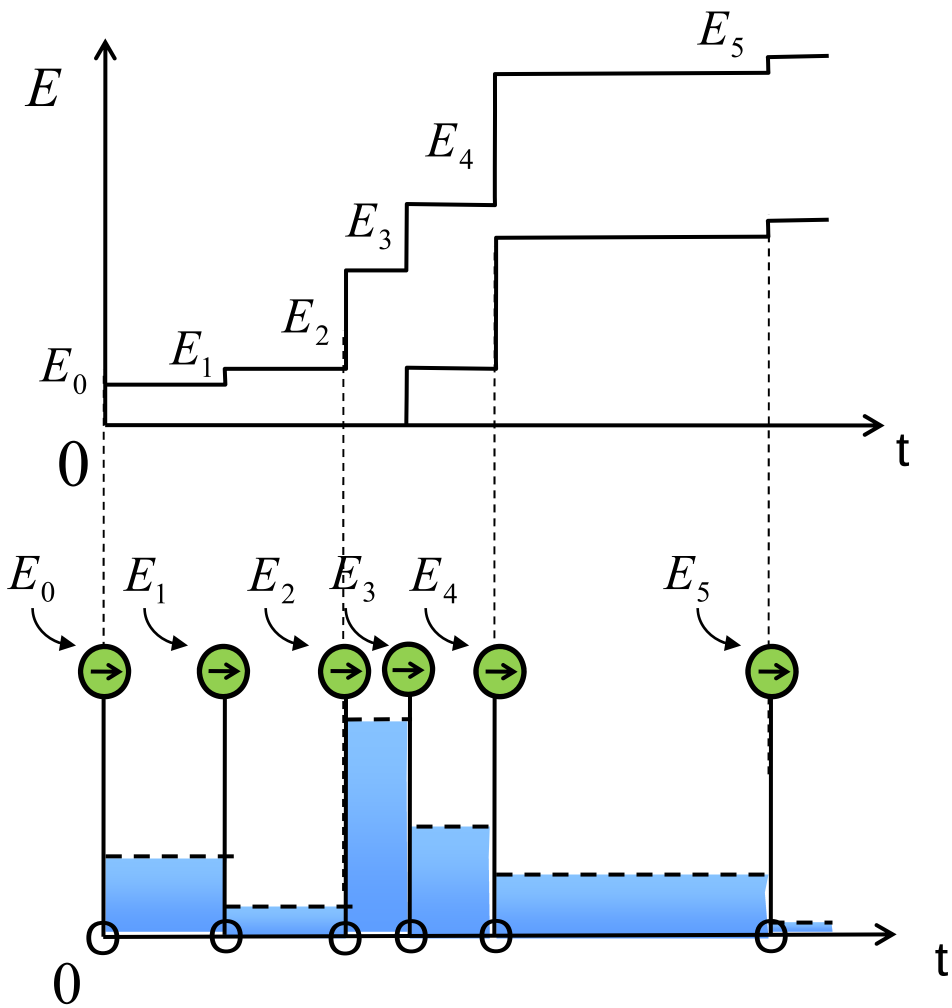
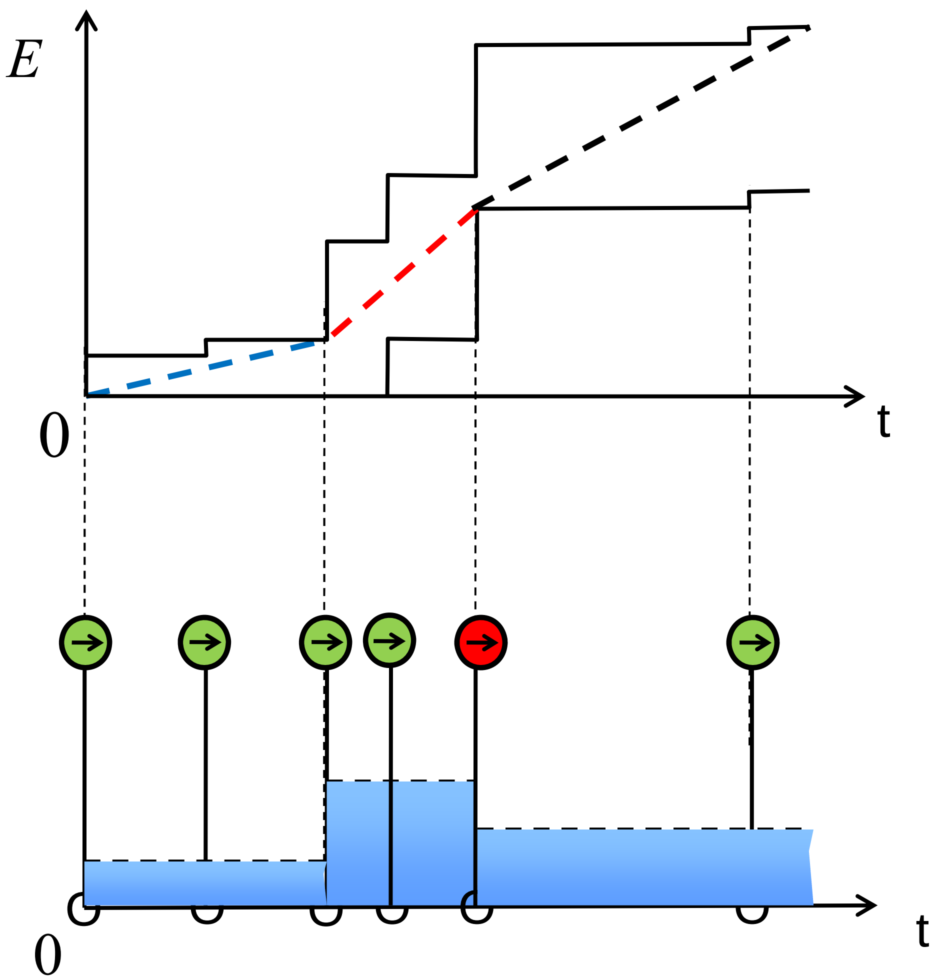
Directional Water-Filling



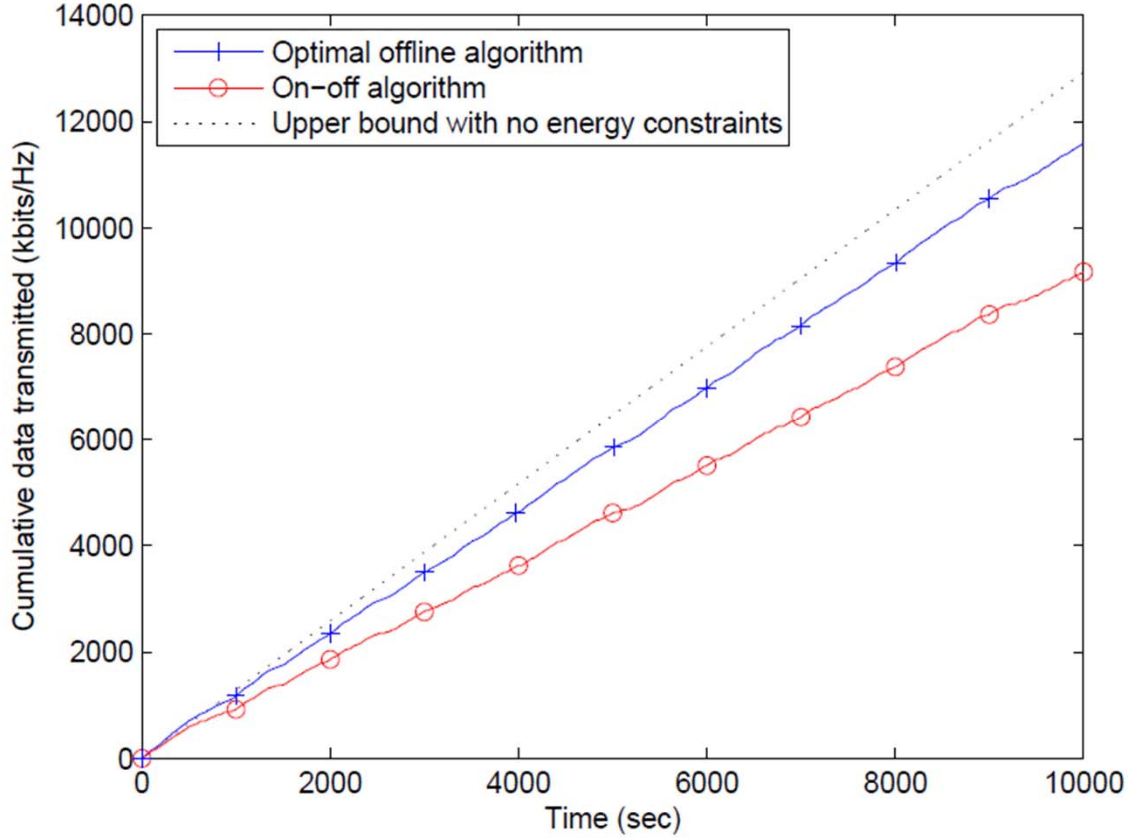
- Energy tunnel and directional water-filling approaches yield the same policy

Directional Water-Filling



- Energy tunnel and directional water-filling approaches yield the same policy

Simulation Results



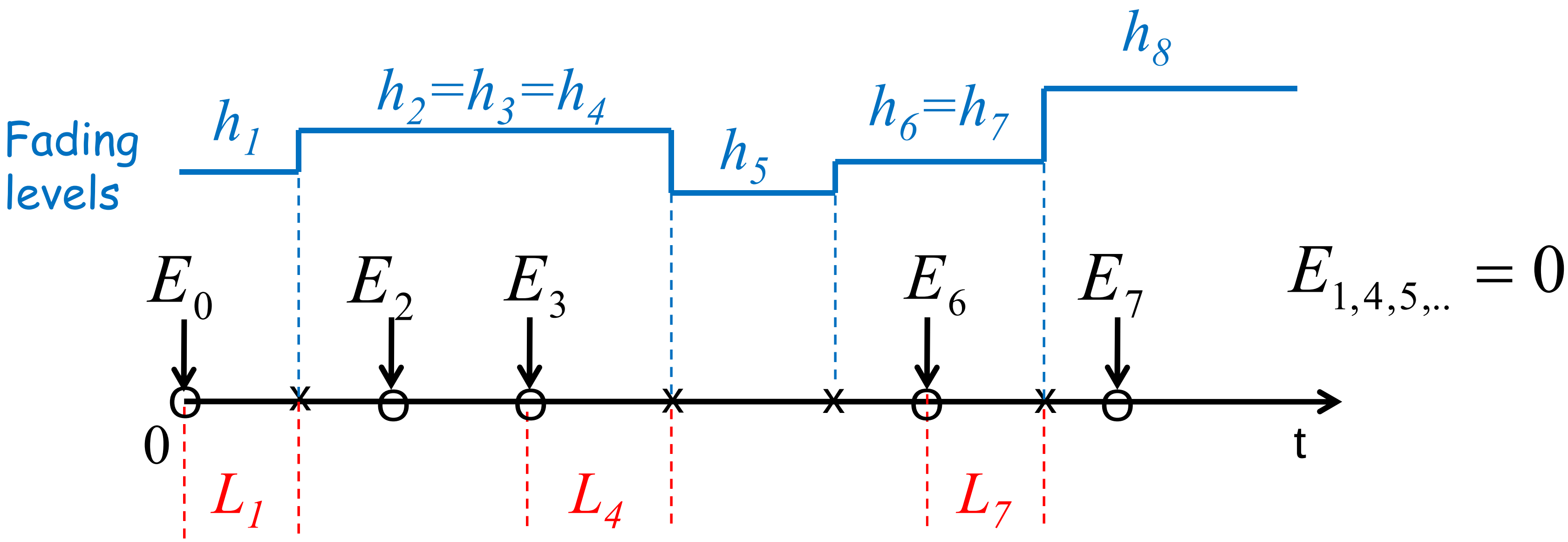
- Improvement of optimal algorithm over an *on-off transmitter* in a simulation with truncated Gaussian arrivals.

Extension to Fading Channels

- [Ozel-Tutuncuoglu-Ulukus-Y.'11]

- Find the short-term throughput maximizing and transmission completion time minimizing power allocations in a fading channel with known channel states.
- Finite battery capacity

System Model



- AWGN Channel with fading h: $r(p,h) = \frac{1}{2}\log(1+hp)$
- Each "epoch" defined as the interval between two "events".

TM Problem with Fading

- Transmission power constant within each epoch:

$$p(t) = \{ p_i, t \in epoch \;\; i, \;\; i = 1, \dots, M \}$$

- Maximize total number of transmitted bits by deadline T

$$\max_{p_i} \sum_{i=1}^{M} \frac{L_i}{2} \log(1 + h_i p_i)$$

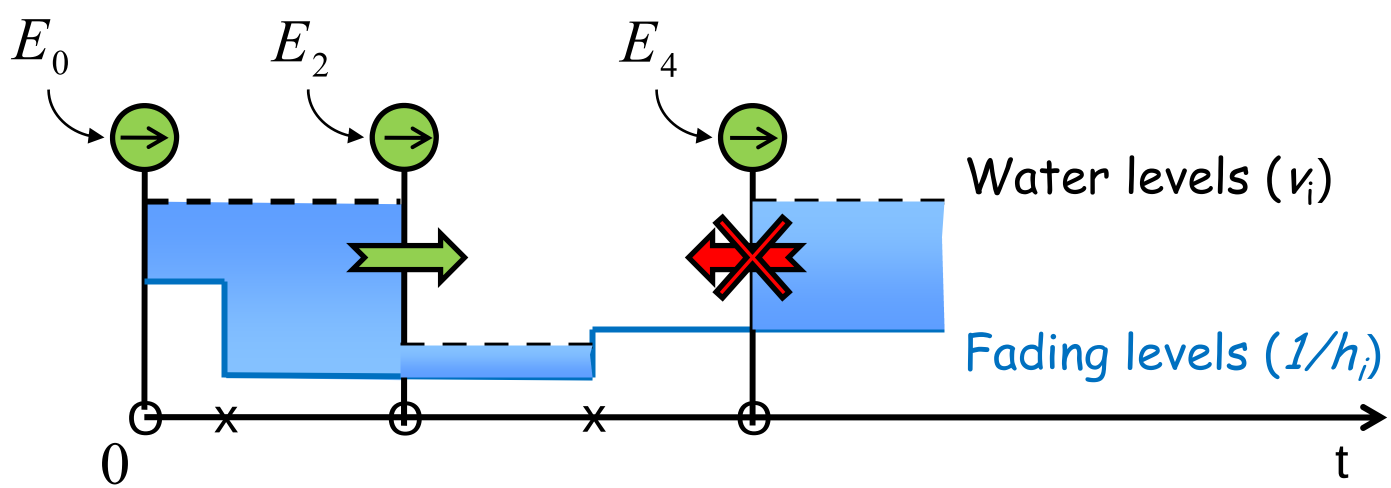
$$s.t. \quad 0 \le \sum_{i=1}^{n} E_i - L_i p_i \le E_{\max} \qquad n = 1, \dots, M$$

- Solution once again is directional waterfilling.

$$p_n^* = \left[\frac{1}{\sum_{i=n}^{M} \lambda_i - \mu_i} - \frac{1}{h_n} \right]^+$$

Directional Water-Filling for fading channels

- Same directional water filling model with added fading levels.
  - Directional water flow **(Energy causality)**
  - Limited water flow **(Battery capacity)**



Multiple EH Transmitters

- How to allocate power when there are **more than one energy harvesting transmitters** sharing the same medium?
- How do the **network parameters** affect the optimal policy?
- Many recent multi-node models, e.g., MAC (and BC) [Ozel,Yang,Ulukus'11,'12], Relay [Cui, Zhang,'12], [Oner, Erkip'13], [Varan, Y.'13], …, Two-way Relay [Tutuncuoglu, Varan, Y.'13],…

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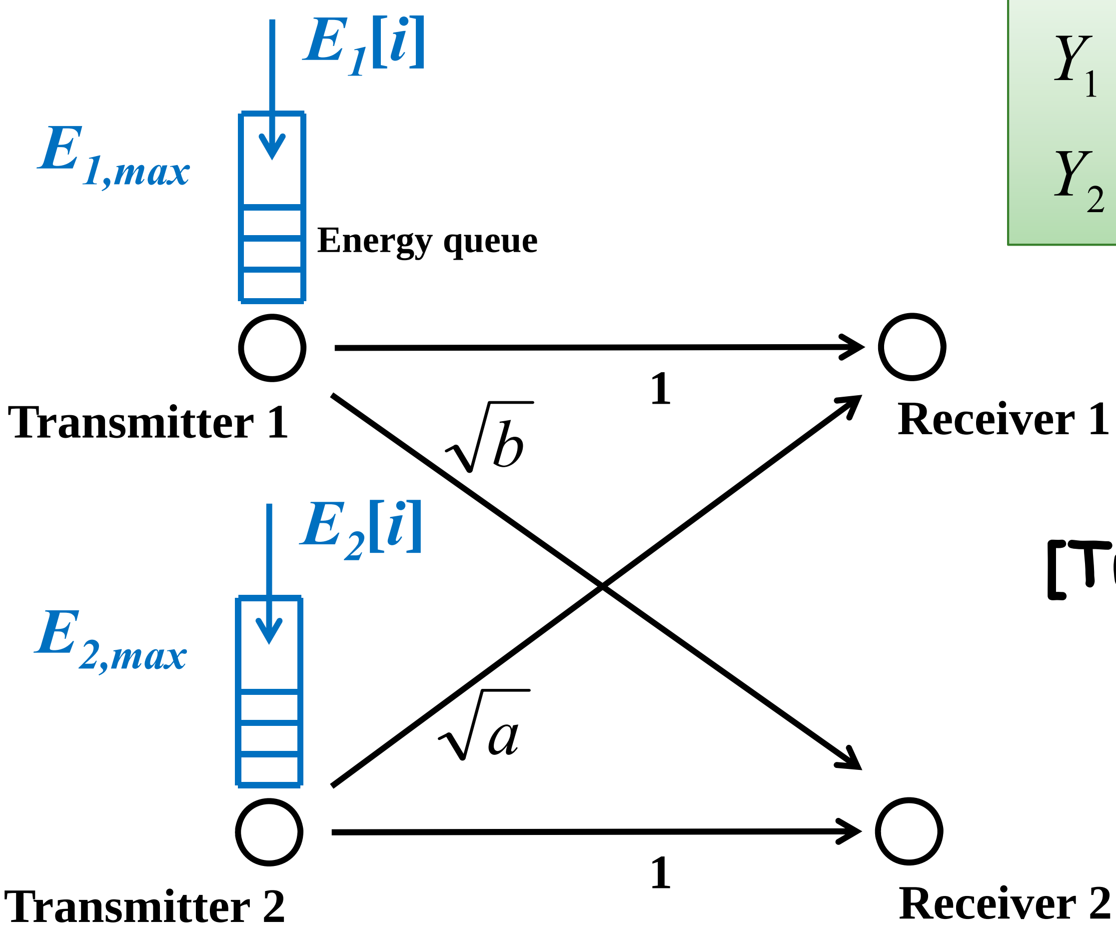
Interference and EH: Gaussian IC with EH Transmitters

$$Y_1 = X_1 + \sqrt{a}X_2 + Z_1$$
$$Y_2 = \sqrt{b}X_1 + X_2 + Z_2$$



[Tutuncuoglu-Y. '12]

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Problem Definition

- **Sum-Throughput Maximization Problem:**

Find optimal transmission power/rate policies that maximize the total amount of data transmitted to both receivers by a deadline ***T*=*Nτ*.**

$$\max_{\mathbf{p}_1 \geq 0, \mathbf{p}_2 \geq 0} \sum_{i=1}^{N} \tau \cdot r(p_1[i], p_2[i])$$

$$s.t. \quad 0 \leq \sum_{i=1}^{n} E_j[i] - \tau \cdot p_j[i] \leq E_{j,\max}$$

$$j = 1,2 \quad n = 1, \ldots, N$$

Concavity of sum-rate

- **Claim:** $r(p_1, p_2)$ is jointly concave in p_1 and p_2

Given any transmission scheme achieving a sum-rate $r(p_1,p_2)$, one can utilize time-sharing to construct concave sum-rate:

$$r^*(p_1, p_2) = \max\left\{\begin{array}{l} r(p_1, p_2), \\ \left\{\begin{array}{l} \lambda \cdot r(p_1', p_2') + (1-\lambda)\cdot r(p_1'', p_2'') \\ s.t.\ \ \lambda \cdot p_j' + (1-\lambda)\cdot p_j'' = p_j,\ 0 \le \lambda \le 1,\ p_j', p_2'' \ge 0 \end{array}\right\} \end{array}\right\}$$

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Optimal Policy

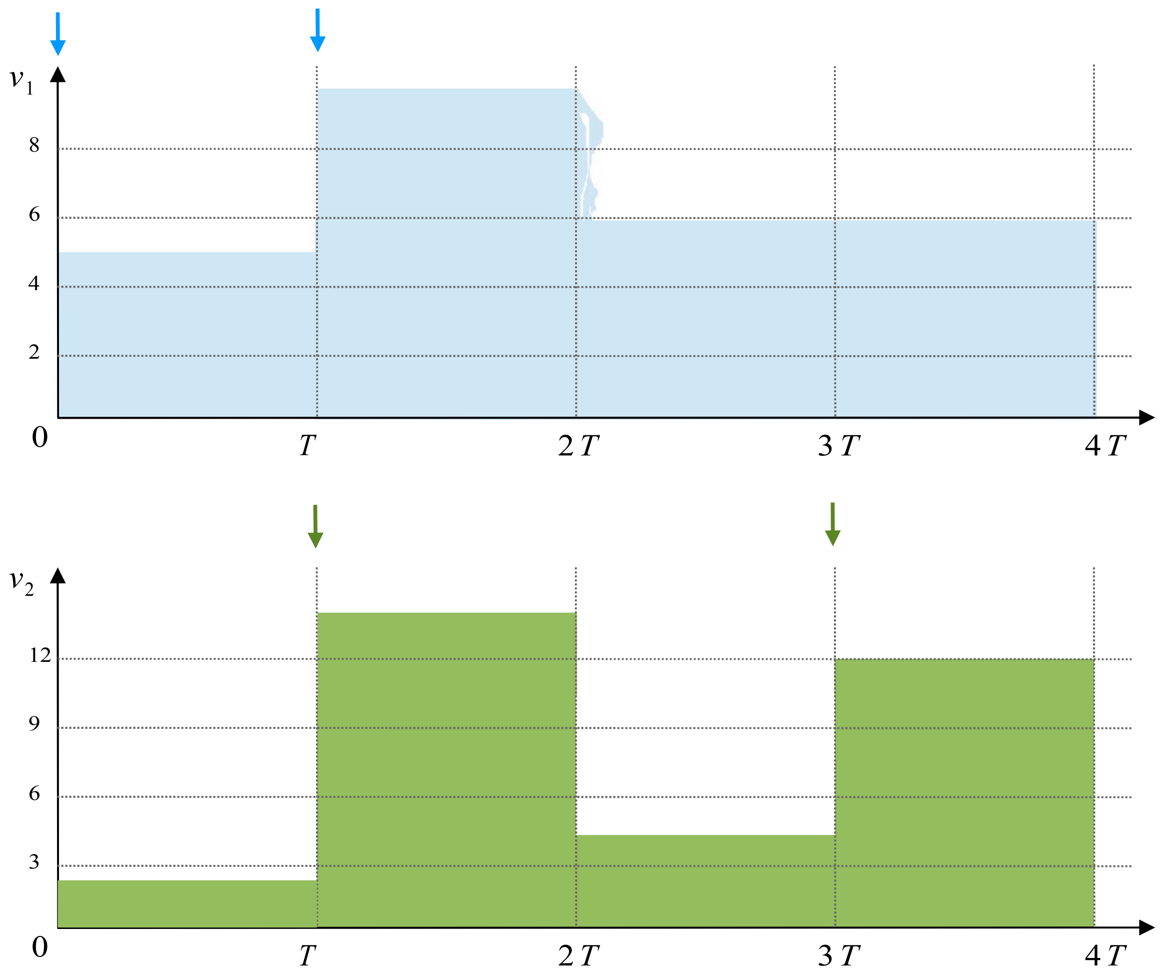
- Convex problem allows the solution to be found using coordinate descent between $p_1[i]$ and $p_2[i]$

Iterative Generalized Directional Water-filling(IGDWF):

constrained water-filling with generalized water levels:

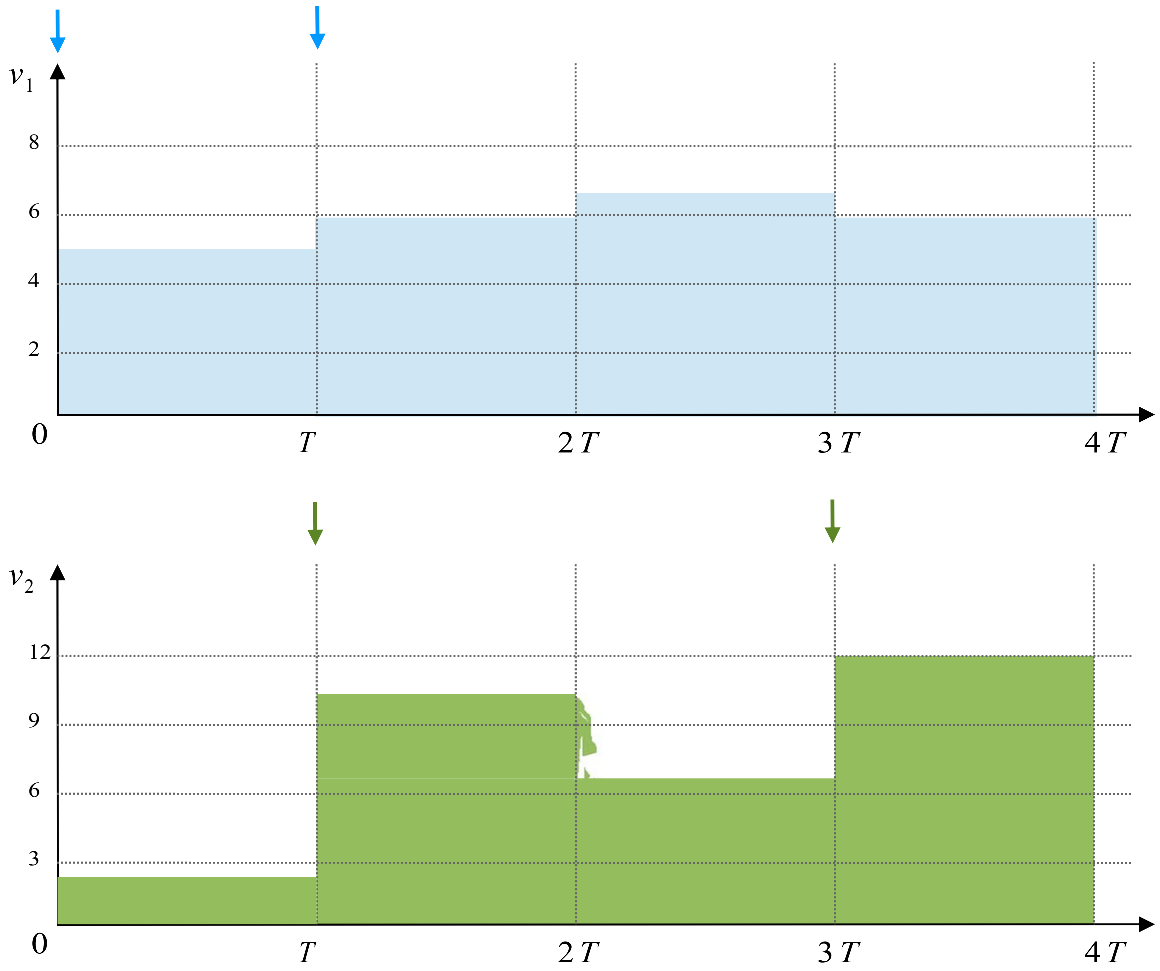
$$v_n = \frac{\partial}{\partial p} r(p)\Big|_{p_n} = \sum_{i=n}^{N} (\lambda_i - \mu_i) - \eta_n$$

Two-user IGDWF



GDWF for User 1

Two-user IGDWF



GDWF for

User 2

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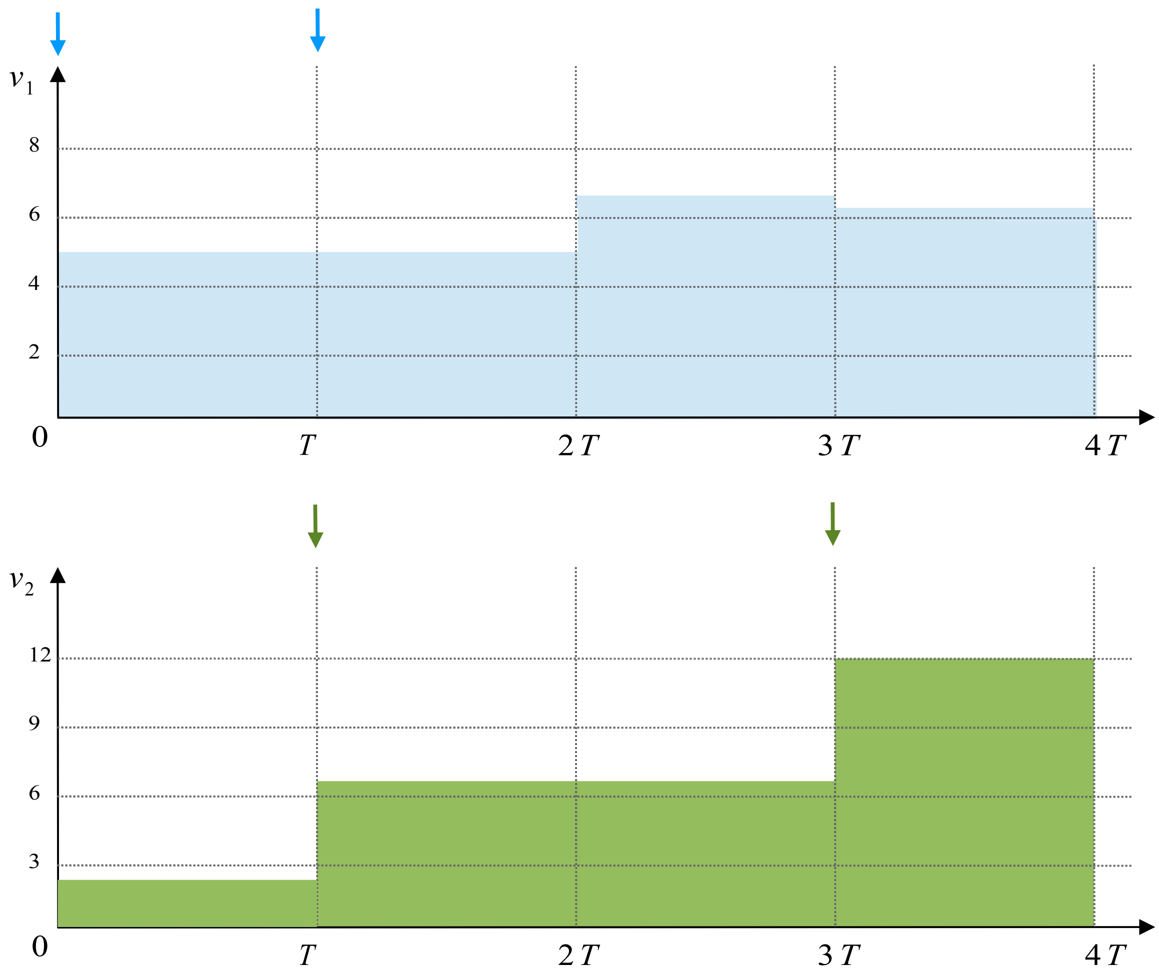
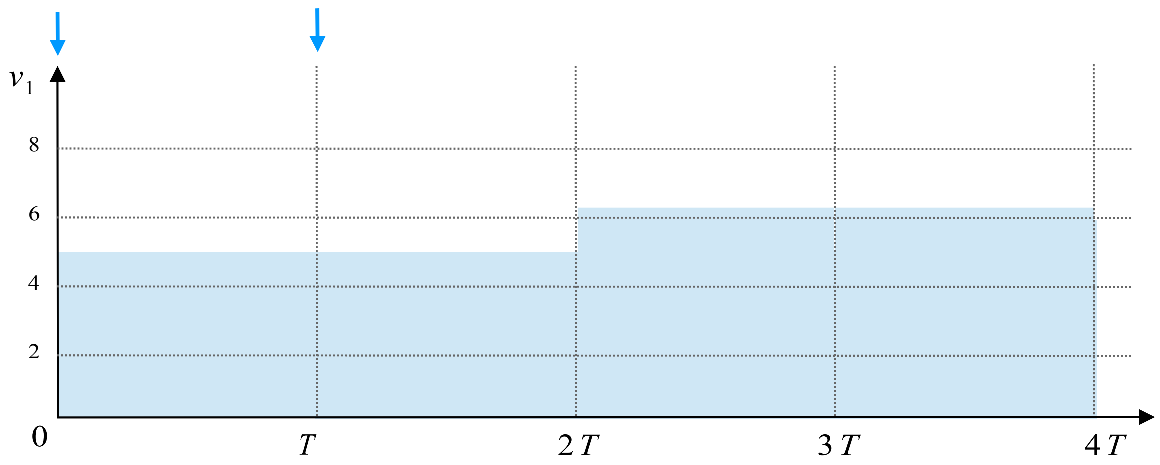
Two-user IGDWF



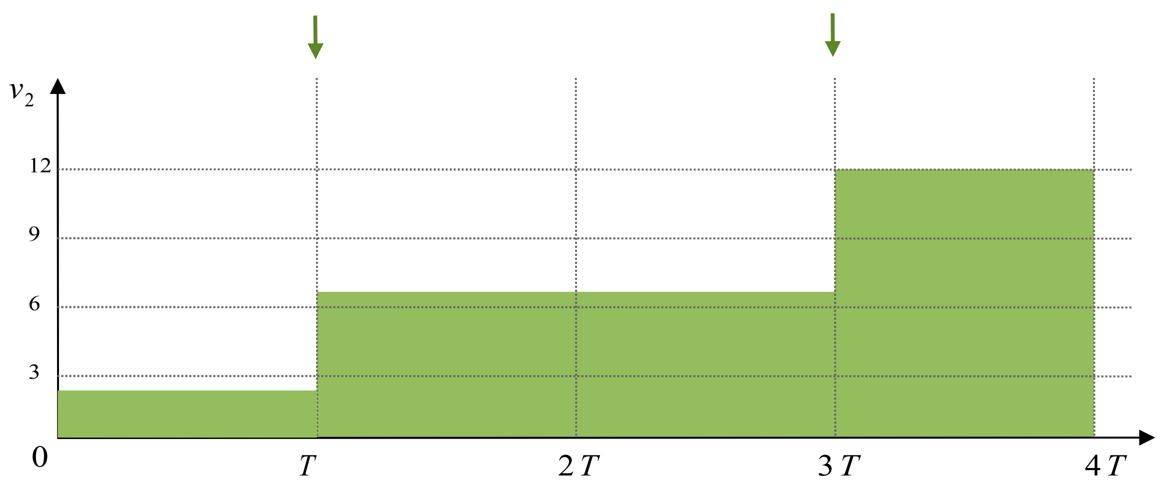
GDWF for

User 1

Two-user IGDWF



GDWF for User 1



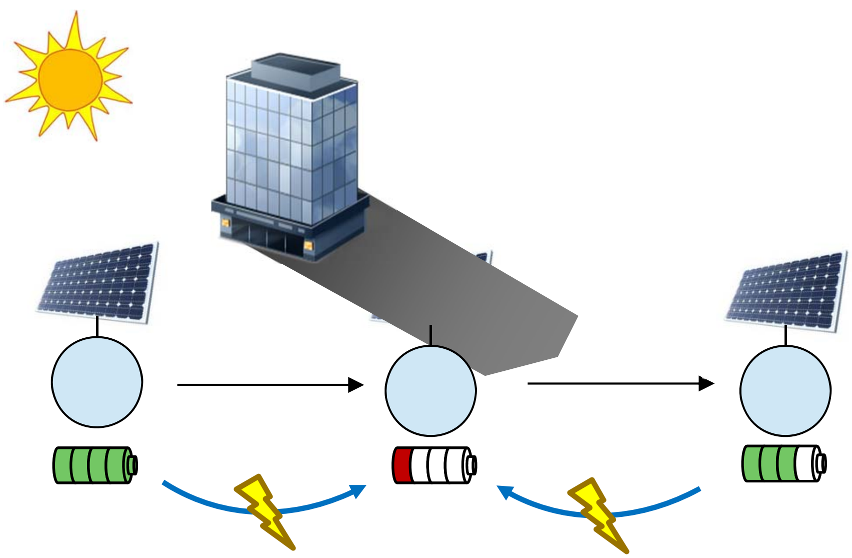
GDWF for User 2

Take-away

- Multiple **energy harvesting transmitters** sharing the same medium: transmit policy of one depends on the others.
- Care need to be exercised in iteratively finding the water-filling solutions.
- Policies do depend heavily on the channels, some instances converge in one iteration and/or result in simplified algorithms, e.g., strong interference.

Multiple EH Transmitters: The concept of Energy Cooperation [Gurakan-Ozel-Yang-Ulukus '12]

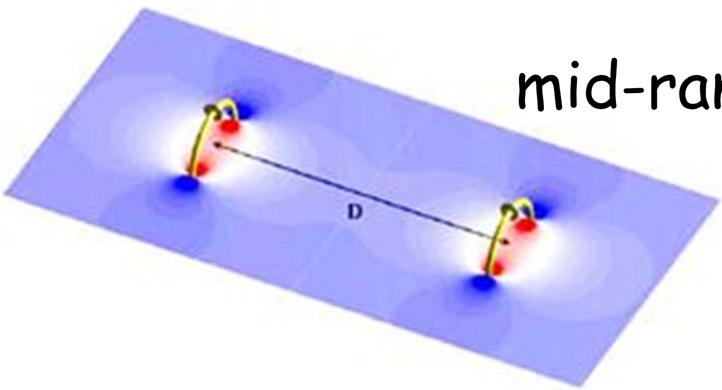
- Intermittent energy $\Rightarrow$ nodes may be energy deprived!

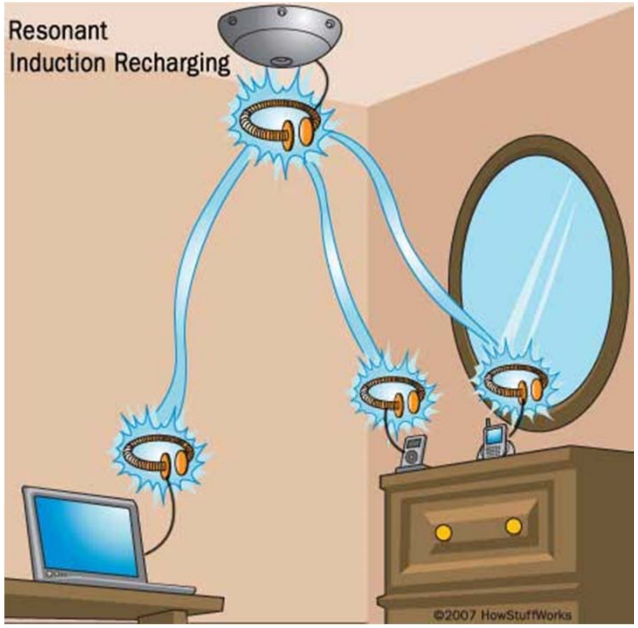


- Relay can "receive" the energy to forward the data.
- Energy cooperation between nodes can be very useful!

Wireless Energy Transfer

- Already present in RFID systems
- New technologies like **strongly coupled magnetic resonance** reported to achieve high efficiency in mid-range



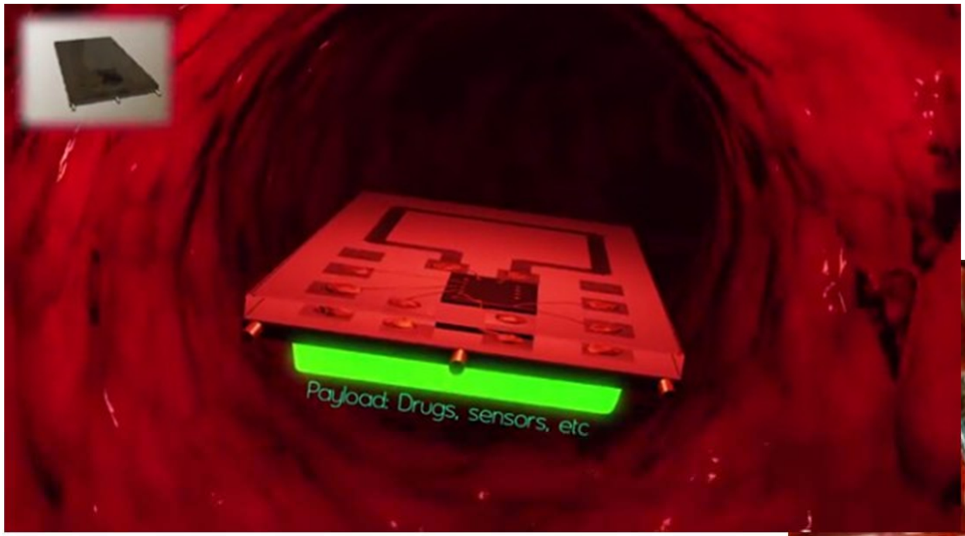


Transfer energy to a 60-watt bulb with 50 percent efficiency from 6-feet & 90 percent efficiency from 3-feet (MIT).
75 percent efficiency from two to three feet away (Intel).

Image Credits: (top) http://www.siongboon.com/projects/2012-03-03_rfid/image/inlay.jpg
(middle) http://www.witricity.com
(bottom) http://electronics.howstuffworks.com/everyday-tech/wireless-power2.htm

Wireless Energy Transfer

In-body (in-vein) wireless devices



Poon, 2012

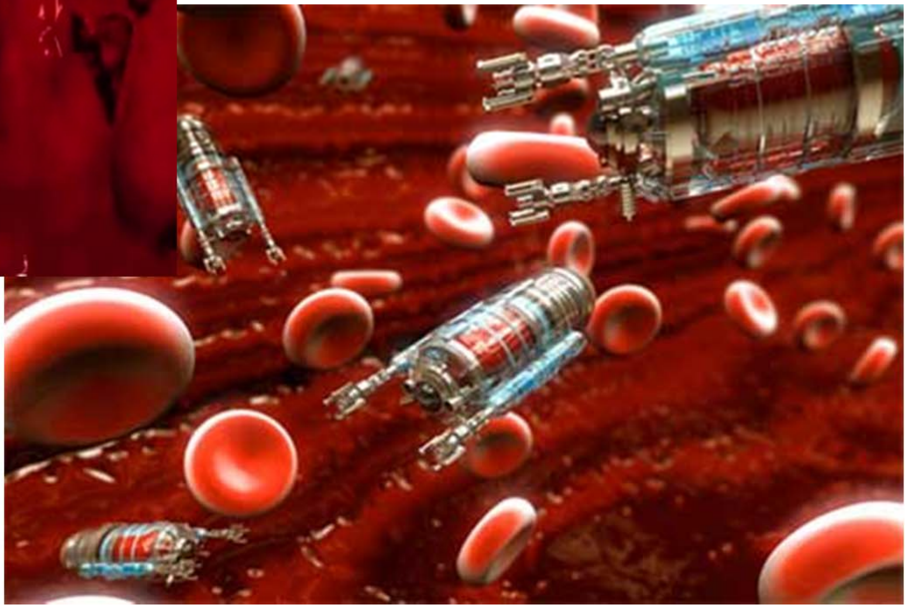
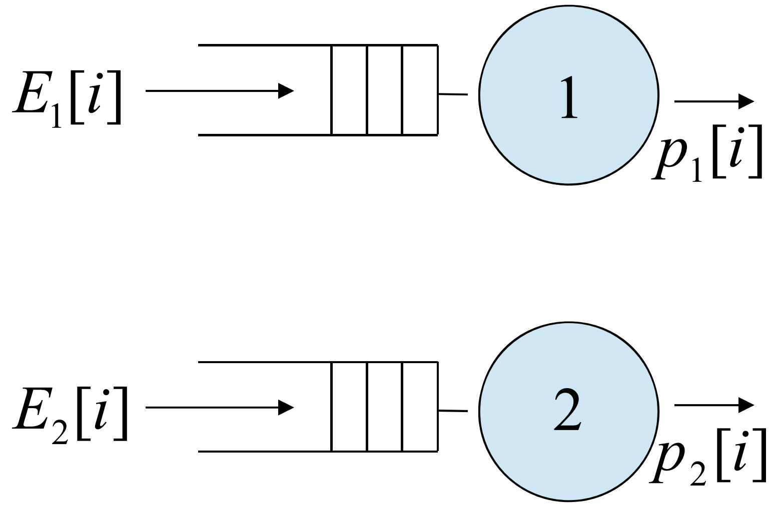


Image Credits: (top) http://www.extremetech.com/extreme/119477-stanford-creates-wireless-implantable-innerspace-medical-device (bottom) http://www.imedicalapps.com/2012/03/robotic-medical-devices-controlled-wireless-technology-nanotechnology/

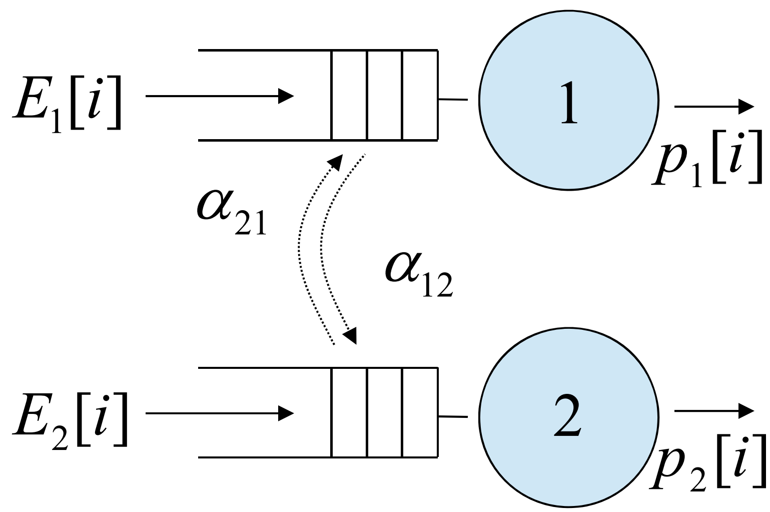
Energy Harvesting and Cooperating Models (EH-EC)



- Time slotted model, N slots with length T, indexed by i
- K transmitters receive energy packets of size $E_j[i]$ at the beginning of the i^{th} time slot
- Received energy stored in an infinite size battery
- In slot i, node k transmits with power $p_k[i]$

EC-EH

- In time slot i, transmitter k sends transmitter j an energy of $\delta_{k,j}[i]$ with efficiency $\alpha_{k,j}$



- Uni-directional energy transfer is a special case with

$$\alpha_{k,j} = 0, \ \alpha_{j,k} > 0, \quad j,k = 1,\dots,K$$

- Energy in node k's battery at the end of the i^{th} time slot:

$$E_k^{bat}[n] = \sum_{i=1}^{n} \left(E_k[i] + \sum_{j=1}^{K} \left(\alpha_{j,k} \delta_{j,k}[i] - \delta_{k,j}[i] \right) - p_k[i] T \right)$$

Harvested energy

Received and sent energy

Energy used for transmission

EC-EH

Energy Constraints:

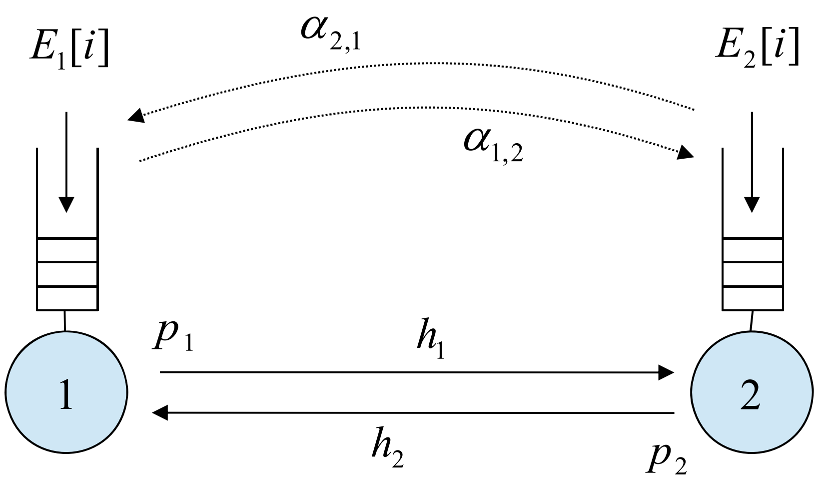
- **Non-negativity** of transmit power and transferred energy: $p_k[n] \geq 0, \quad \delta_{j,k}[n] \geq 0, \quad j,k = 1,\ldots,K, \quad n = 1,\ldots,N$

- **Energy Causality**: Energy required by transmission or transfer is available, i.e., harvested:

$$E_k^{bat}[n] = \sum_{i=1}^{n} \left(E_k[i] + \sum_{j=1}^{K} \left(\alpha_{j,k} \delta_{j,k}[i] - \delta_{k,j}[i] \right) - p_k[i]T \right) \geq 0$$

- **What is the sum-capacity of EC-EH-MAC and EC-EH-T(wo)-W(ay)-C?**

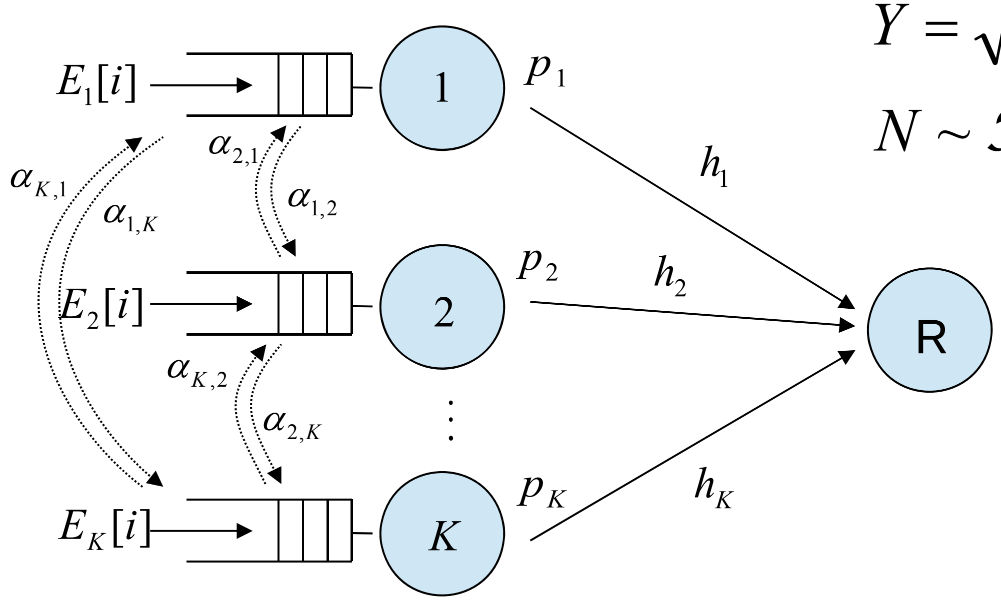
EC-EH-TWC



$$Y_1 = X_1 + \sqrt{h_2} X_2 + N_1$$
$$Y_2 = X_2 + \sqrt{h_1} X_1 + N_2$$
$$N_k \sim \mathcal{N}(0, \sigma_k^2),$$

- **Sum-Capacity:** $C_S^{TWC} = \frac{1}{2}\log(1 + p_1) + \frac{1}{2}\log(1 + p_2)$

EC-EH-MAC



$$Y = \sqrt{h_1} X_1 + \ldots + \sqrt{h_K} X_K + N$$
$$N \sim \mathcal{N}(0, \sigma^2),$$

Normalize σ^2 and h_k by:

$$Y' = \frac{Y}{\sigma}, \quad X' = X \frac{\sqrt{h_k}}{\sigma}$$

- **Sum-Capacity:** $C_S^{MAC} = \frac{1}{2} \log\left(1 + \sum_{k=1}^{K} p_k\right)$

Problem Statement

[Tutuncuoglu-Y. '13]

- Find maximum achievable sum-rate by optimizing the energy transfer <u>and</u> energy expended for tx.

$$\max_{p_k[n],\,\delta_{k,j}[n]} \frac{1}{N}\sum_{i=1}^{N} C_S(p_1[i], p_2[i], \ldots, p_K[i])$$

$$s.t.\ \ \delta_{k,j}[n] \geq 0,\ \ p_k[n] \geq 0,$$

$$\sum_{i=1}^{n}\left(E_k[i] + \sum_{j=1}^{K}\left(\alpha_{j,k}\delta_{j,k}[i] - \delta_{k,j}[i]\right) - p_k[i]T \right) \geq 0$$

$$j,k = 1,\ldots,K, \quad n = 1,\ldots,N$$

Simplifying the Problem

1) Optimal Routing of Energy Transfers:

Use equivalent transfer efficiency values that reflect the optimal routing of energy transfers.

2) Procrastinating Policies:

Restrict to a subset of policies that delay energy transfer unless transferred energy is used immediately

3) Decomposition:

Solve energy transfer and power allocation separately

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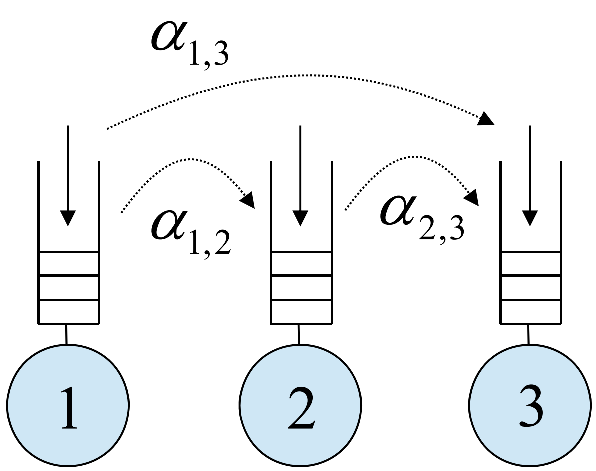
Routing Energy Transfers



- Energy can be transferred through multiple paths.
- Optimal policy chooses the **highest efficiency path.**
- Transferring and receiving energy simultaneously is suboptimal.

- Redefine **effective** efficiency values as

$$\overline{\alpha}_{k,j} = \max_{(e_1,\ldots,e_m)} \alpha_{k,e_1}\alpha_{e_1,e_2}\ldots\alpha_{e_m,j}$$

where $(k, e_1, e_2, \ldots, e_m, j)$ is any feasible energy transfer path

Procrastinating Policies

- **Definition:** A **procrastinating policy** satisfies

$$p_j[i]T \geq \sum_{k=1}^{K} \alpha_{k,j}\delta_{k,j}[i]$$

i.e., the energy received by a node is not greater than the energy required for transmission within that time slot.

- In a procrastinating policy, a node ***does not transfer energy unless the receiving node intends to use it immediately.***
- **Lemma:** There exists at least one procrastinating policy that solves the sum-capacity problem.
- ➔ Restrict search space to such policies

Sum-Capacity Problem

- Define **consumed powers** $\bar{p}_k[i] = p_k[i] + \frac{1}{T}\sum_{j=1}^{K} \delta_{k,j}[i] - \alpha_{j,k}\delta_{j,k}[i]$
- Sum-Capacity problem can be **decomposed** as

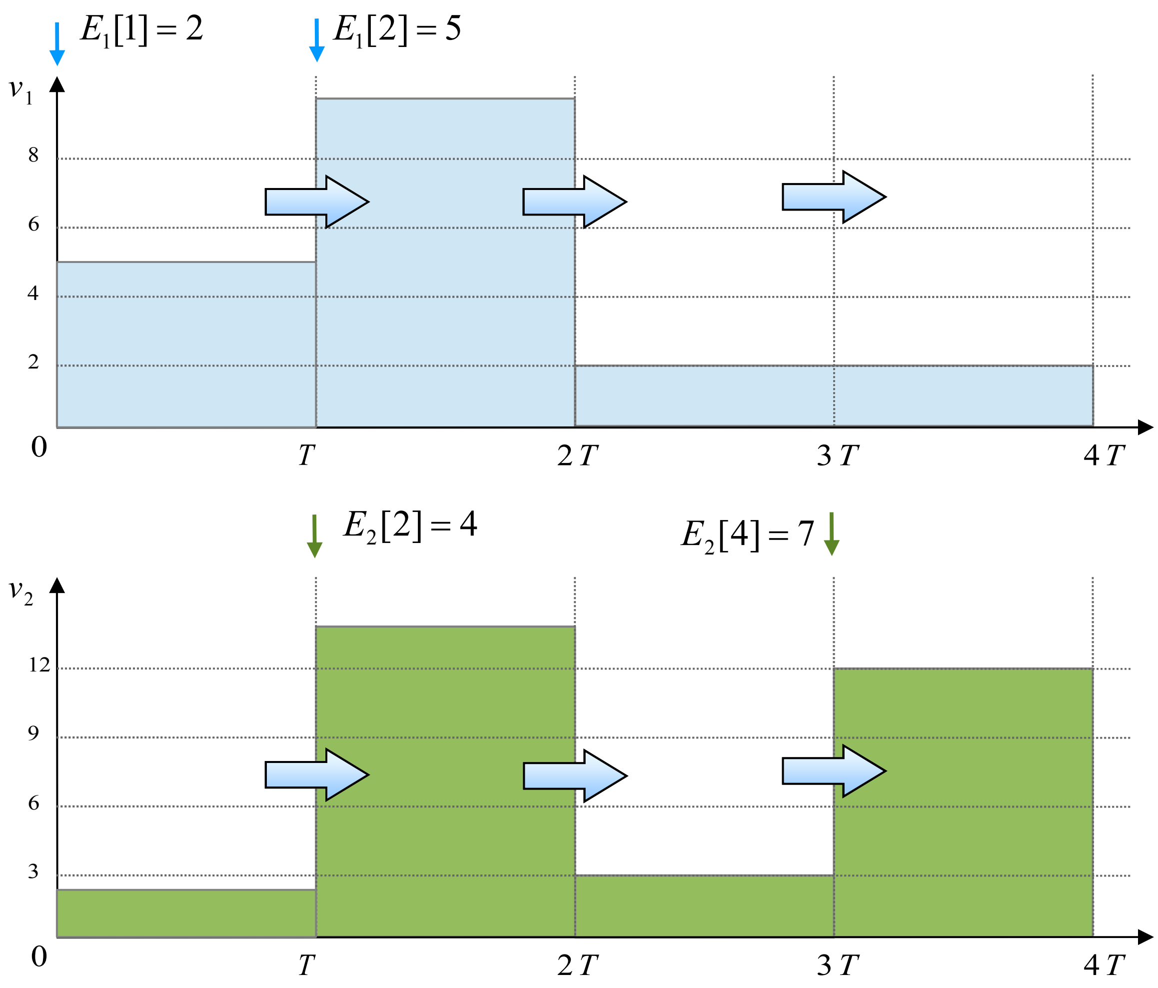
$$\max_{\bar{p}_k[n]} \frac{1}{N}\sum_{i=1}^{N} C_S^*(\bar{p}_1[i],\ldots,\bar{p}_K[i])$$
$$s.t.\quad \bar{p}_k[n] \geq 0,$$
$$\sum_{i=1}^{n}\left(E_k[i] - \bar{p}_k[i]T\right) \geq 0$$
$$k = 1,\ldots,K,\quad n = 1,\ldots,N$$

$$C_S^* = \max_{\delta_{k,j}[i]} C_S\left(\bar{p}_k[i] - \frac{1}{T}\sum_{j=1}^{K}(\delta_{k,j}[i] - \alpha_{j,k}\delta_{j,k}[i])\right)$$
$$s.t.\quad \delta_{k,j}[i] \geq 0,\quad \bar{p}_k[i]T \geq \sum_{j=1}^{K}\delta_{k.j}[i]$$
$$j,k = 1,\ldots,K$$

Power Allocation
Solved via IGDWF

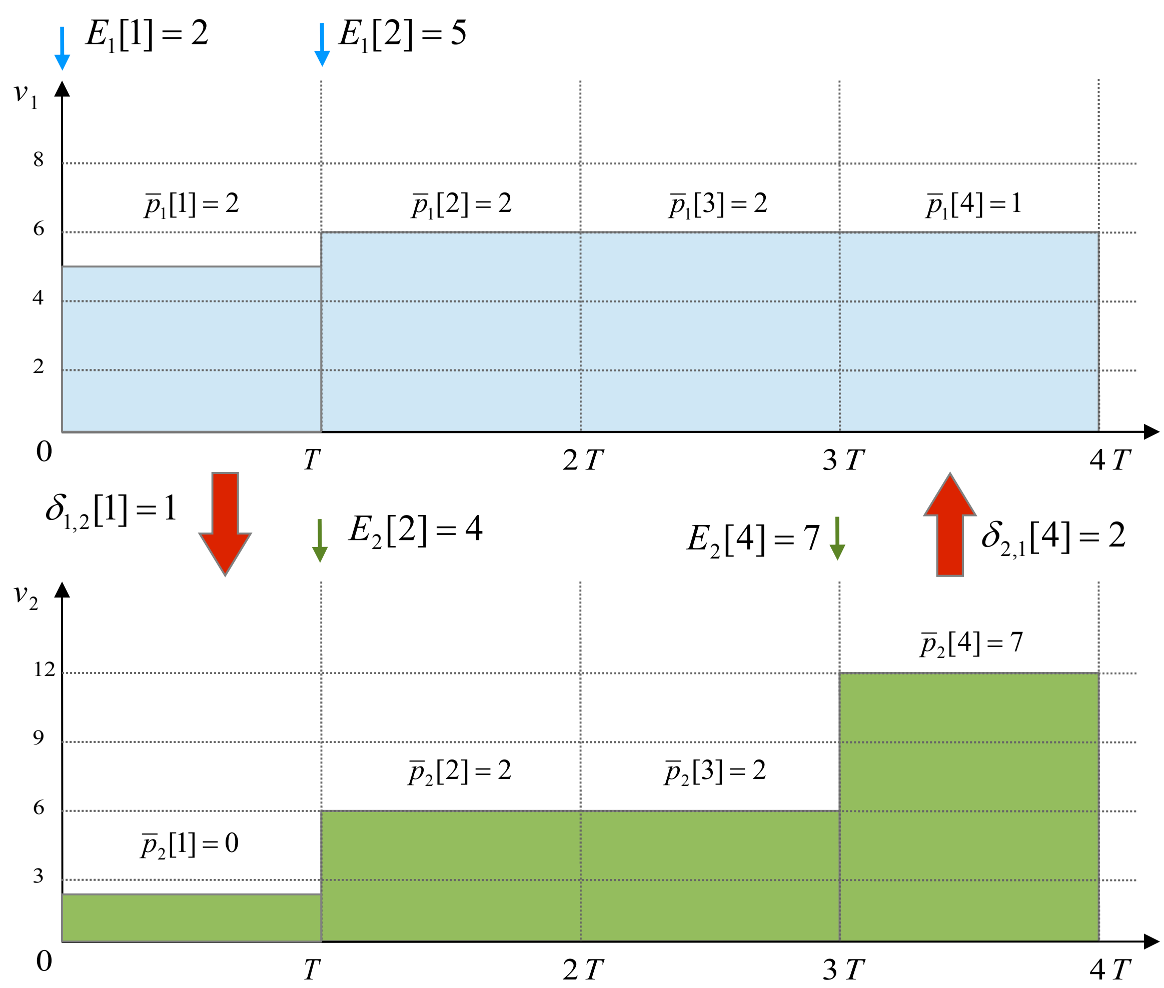
Energy Transfer
Solved directly (single slot)

EC-EH-TWC



$$\alpha_{1,2} = \alpha_{2,1} = 0.5$$

EC-EH-TWC



$$\alpha_{1,2}=\alpha_{2,1}=0.5$$

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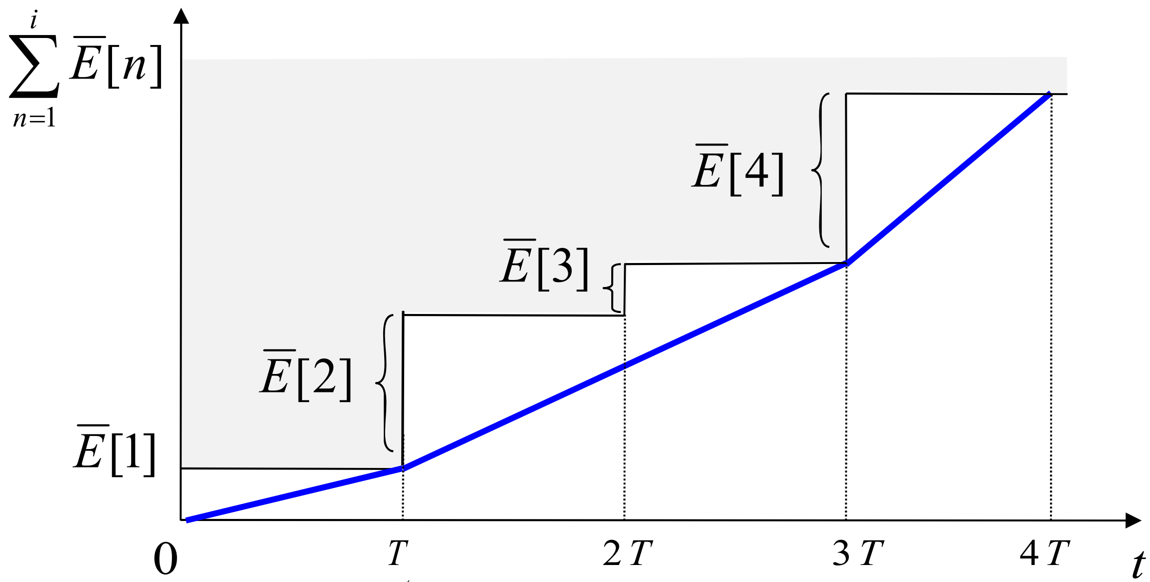
EC-EH-MAC

- **Energy transfer direction** is determined by $a_k = \max_j \alpha_{k,j}$
- **Power allocation problem** is solved as if a single transmitter with energy arrivals $$\bar{E}[i] = \sum_{k=1}^{K} a_k E_k[i]$$



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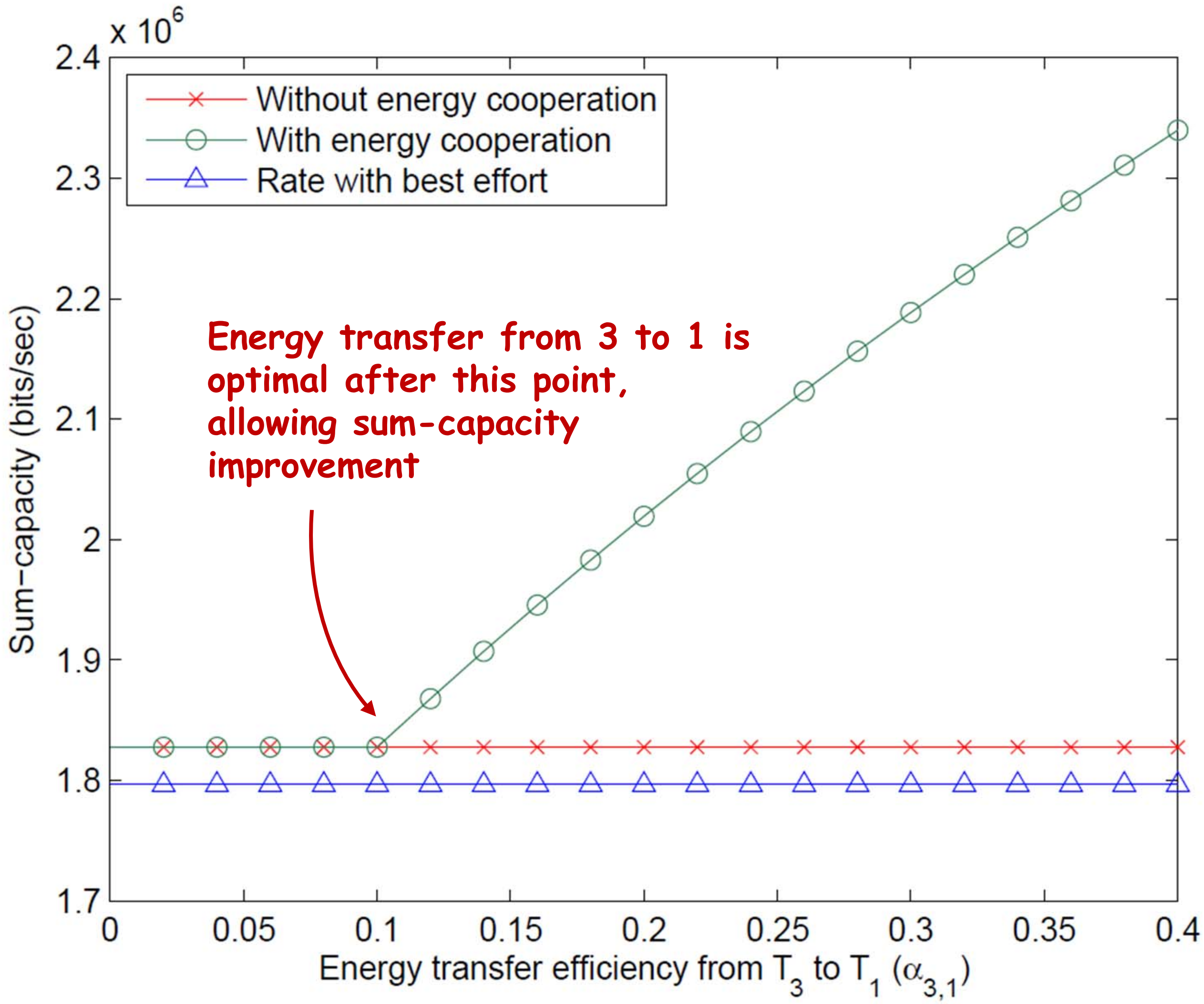
Simulations

- *MAC*

$$N = 100,\ \ T = 1\sec,$$
$$h_1 = -100dB,$$
$$h_2 = -105dB,$$
$$h_3 = -110dB,$$
$$N_0 = 10^{-19}W/Hz$$
$$E_1[i] \sim U[0,1]mJ,$$
$$E_2[i], E_3[i] \sim U[0,10]mJ,$$
$$[\alpha_{k,j}] = \begin{bmatrix} 1 & 0.3 & 0.2 \\ 0.1 & 1 & 0.4 \\ \alpha_{3,1} & 0 & 1 \end{bmatrix}$$



TWC-Simulations

$N = 100,\ T = 1\sec,$

$h_1 = -100dB,$

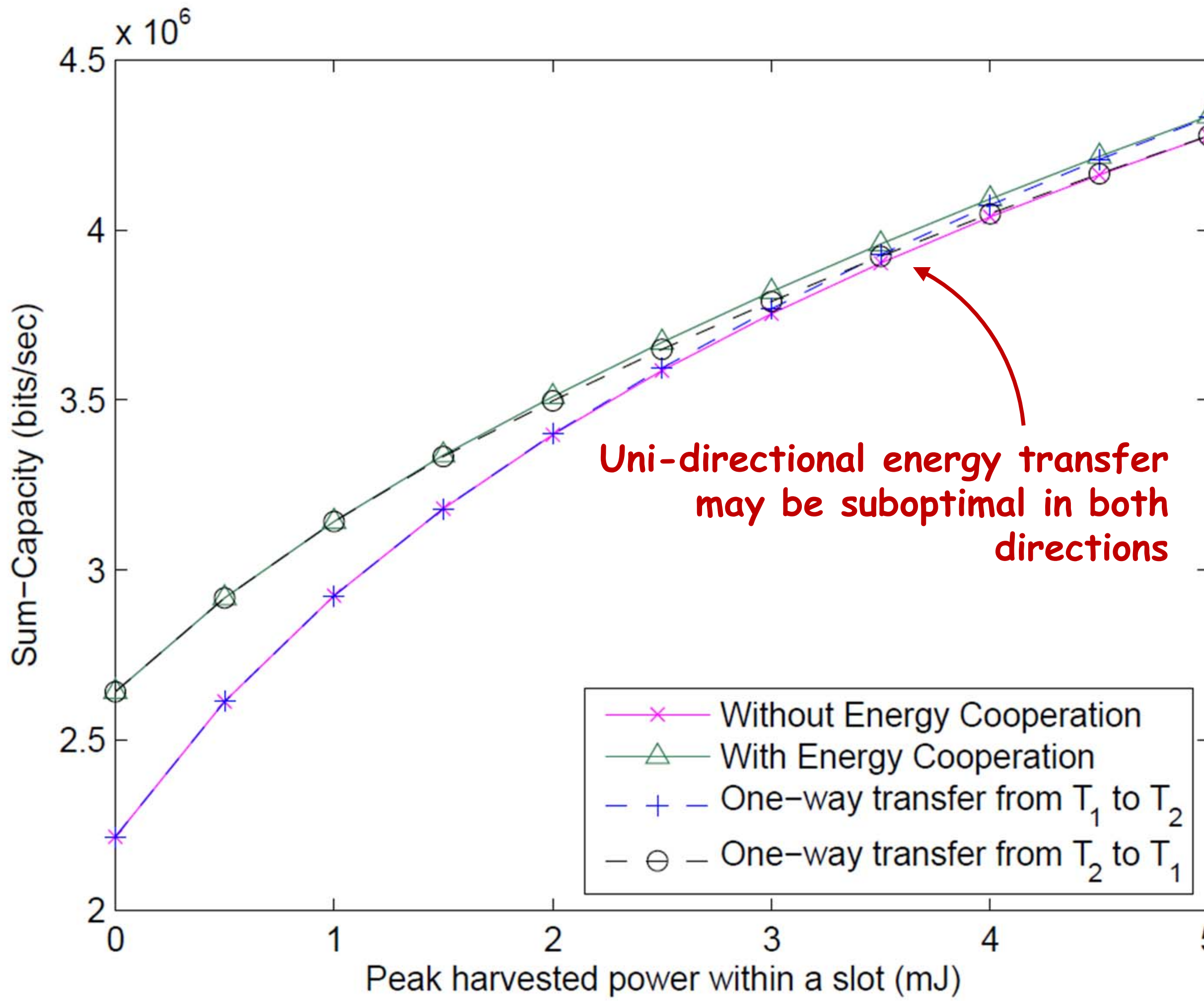
$h_2 = -100dB,$

$N_0 = 10^{-19} W / Hz$

$E_1[i] \sim U[0, Eh]mJ,$

$E_2[i] \sim U[0,10]mJ,$

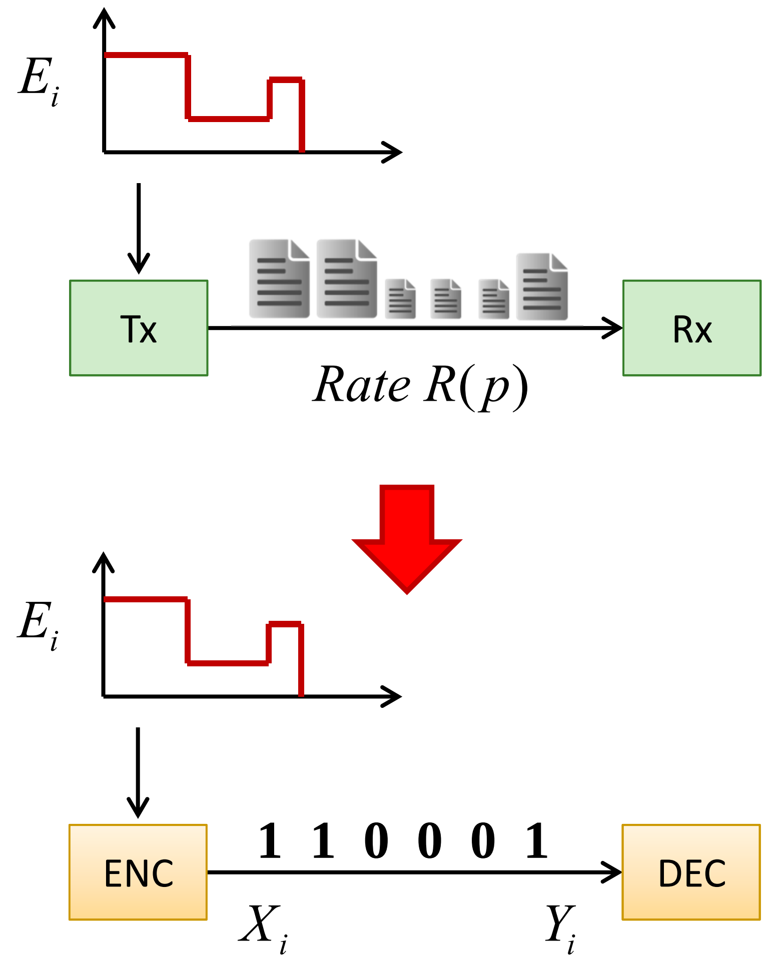
$a_{1,2} = 0.5,\ a_{2,1} = 0.5$



Information Theory of EH Transmitters

- So far, we have assumed **sufficiently long time slots** and utilized the known rate expressions.

- What if **energy harvesting is at the channel use level**, i.e., each input symbol is individually limited by EH constraints?

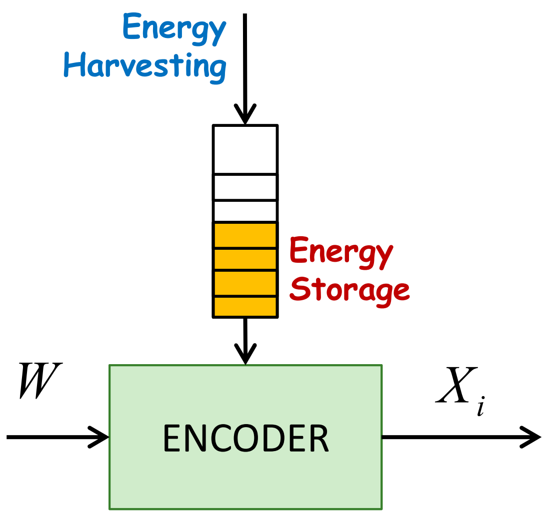


Information Theory of EH Transmitters

Energy Harvesting (EH) Channel:

[Tutuncuoglu-Ozel-Ulukus-Y.'13]

- The **channel input** is restricted by an external **energy harvesting** process.
- **State:** available energy
  - Has **memory** (due to energy storage)
  - **Depends on channel input**
  - **Causally known to Tx (causal CSIT)**



EH Channel

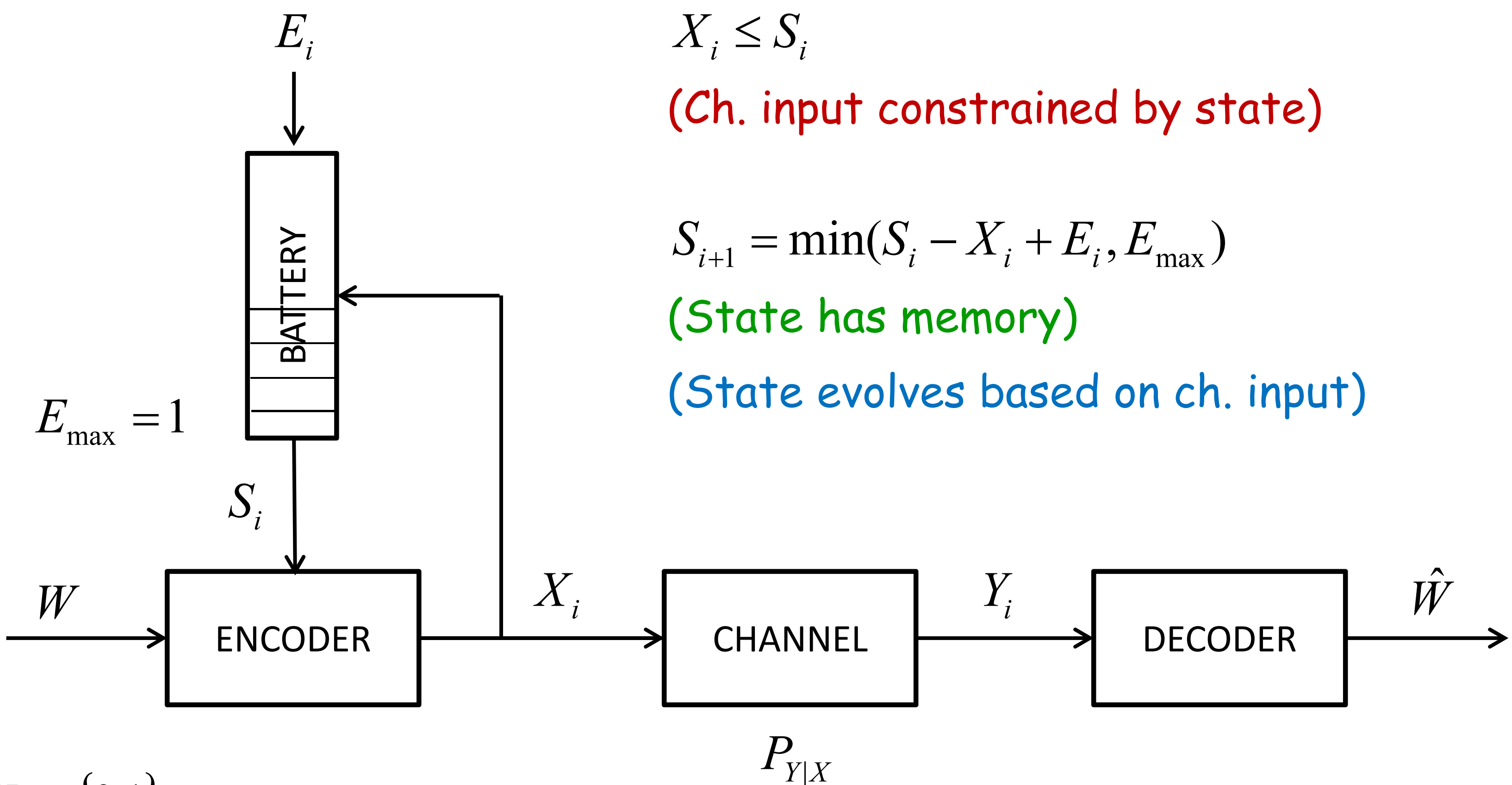
$X_i \le S_i$

(Ch. input constrained by state)

$S_{i+1} = \min(S_i - X_i + E_i, E_{\max})$

(State has memory)

(State evolves based on ch. input)



$X_i \in \{0,1\}$

PENNSTATE

Capacity with Zero Storage

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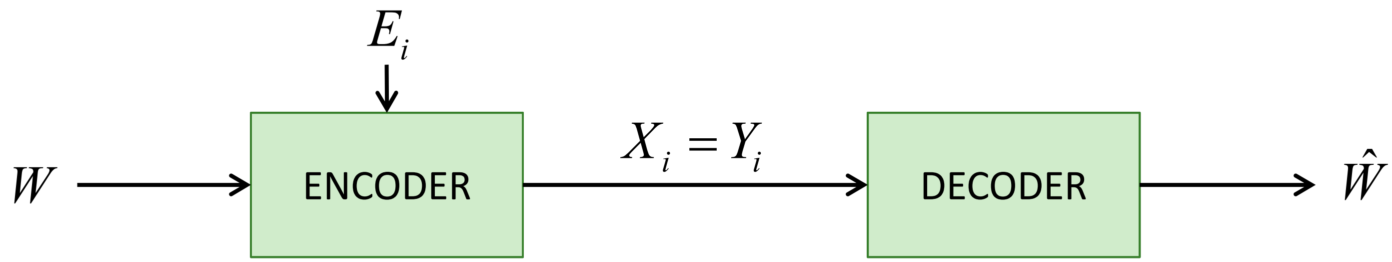


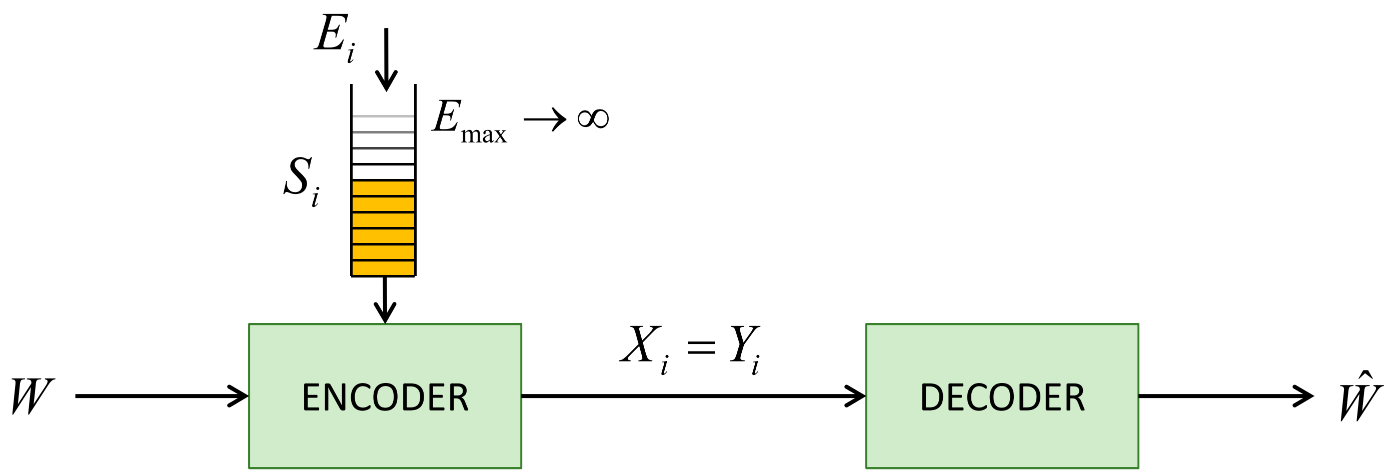
- Let $E_{\max} = 0$, and encoder can use arriving energy, i.e.,

$$\begin{aligned} &if \quad E_i = 0, \ \ then \quad X_i = 0, \\ &if \quad E_i = 1, \ \ then \quad X_i \in \{0,1\}. \end{aligned}$$

- **Memoryless channel with causal state,** [Shannon 1958]

$$C_{ZS} = \max_p H(pq) - pH(q)$$

Capacity with Infinite Storage



- As $E_{\max} \to \infty$, a **save-and-transmit scheme** proposed for the AWGN ch [Ozel, Ulukus, 12] is optimal.
- Any codeword with $\mathrm{E}[X] \le p$ can be conveyed without error

$$C_{IS} = \begin{cases} H(q), & q \le \frac{1}{2} \\ 1, & q > \frac{1}{2} \end{cases}$$

The Binary EH Channel

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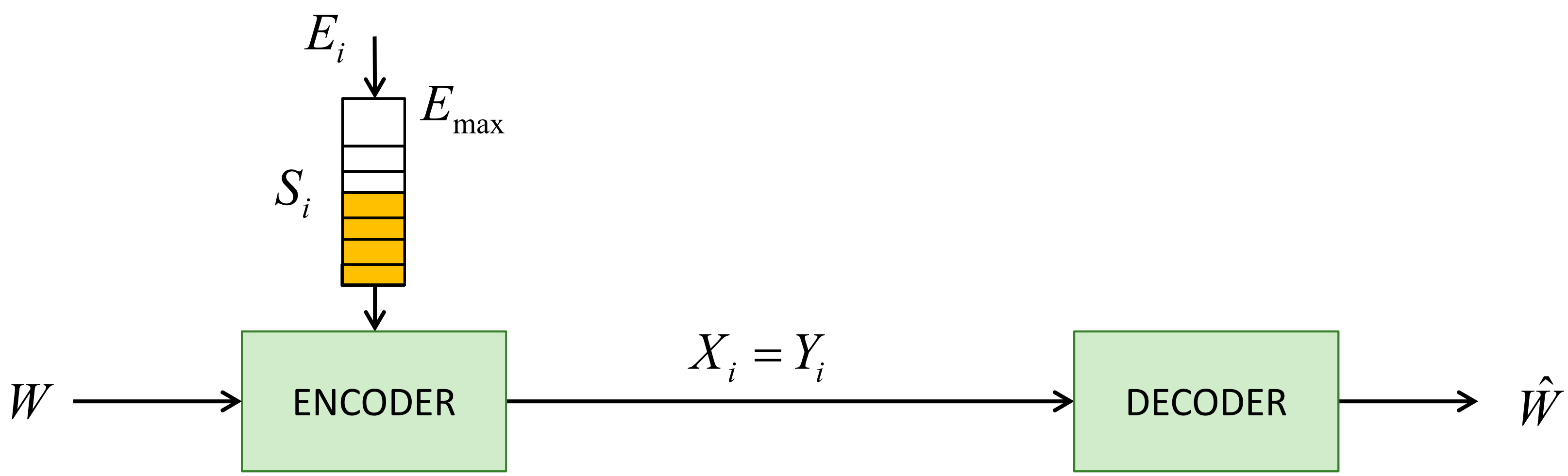


[Tutuncuoglu-Ozel-Y.-Ulukus'13]

- Unit battery, $E_{\max} = 1$
- Binary noiseless channel, $X_i = Y_i$
- Timing channel equivalent: encoding strategy; upper bound by providing state info at the decoder.

New Results on BEHC [Tutuncuoglu-Ozel-Y.-Ulukus'14] (will be presented at ISIT 2014)

- A tighter upper bound than [Tutuncuoglu-Ozel-Y.-Ulukus'13]:

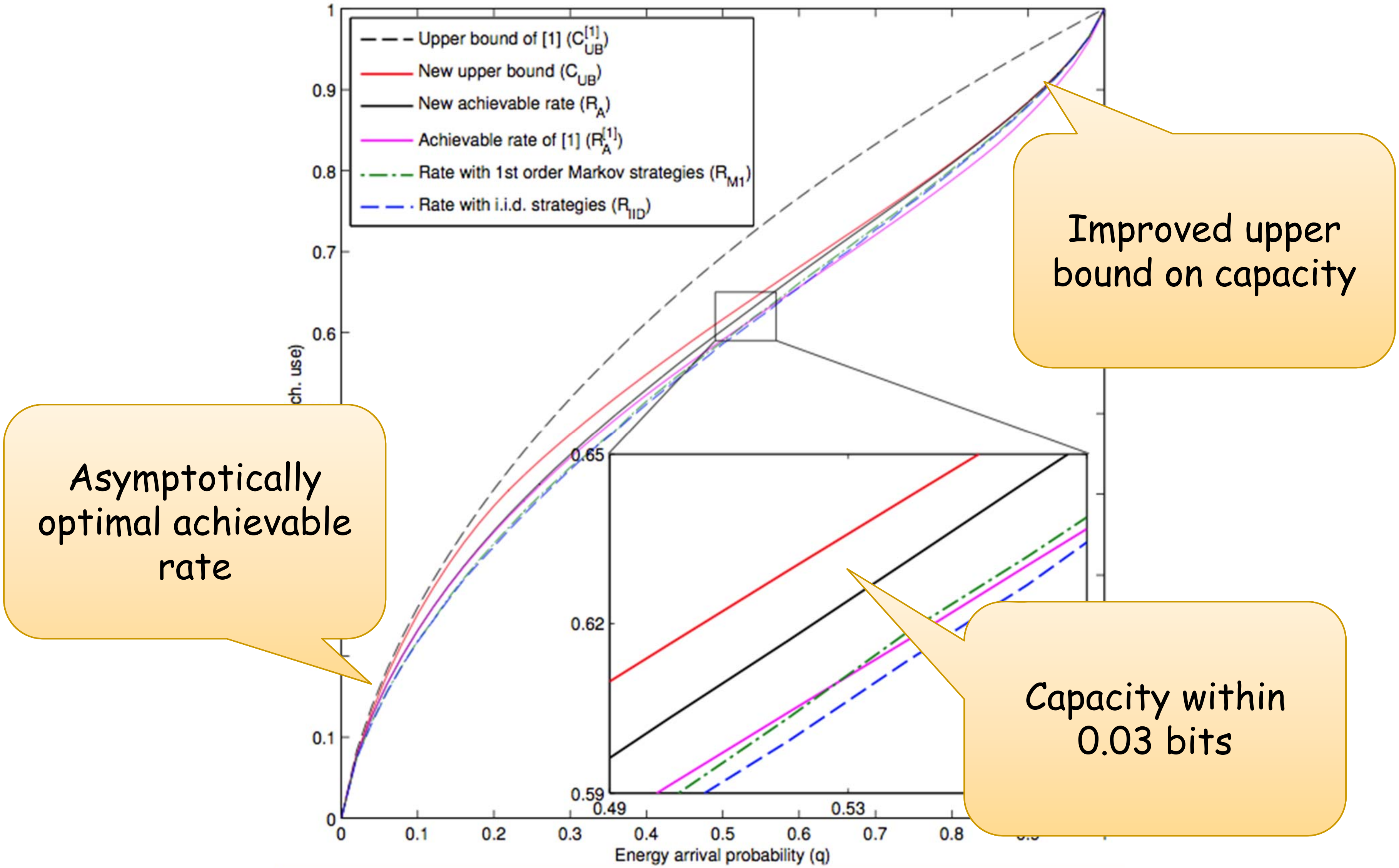
$$C_{BEHC} \leq \max_{p_T(t) \in \mathrm{P}} \frac{H(T) - \boxed{\sum_{t=1}^{\infty} \frac{H((1-q)^t)}{1-(1-q)^t} p_T(t)}}{E[T]}$$

A lower bound on $I(Z;T|U)$
i.e., the information leaked to the receiver about the harvesting process.

- Improved encoding scheme as well:

$$V = \begin{cases} U - Z + 1 & U \geq Z \\ (U - Z \bmod N) + 1 & U < Z \end{cases}$$

New Results on BEHC



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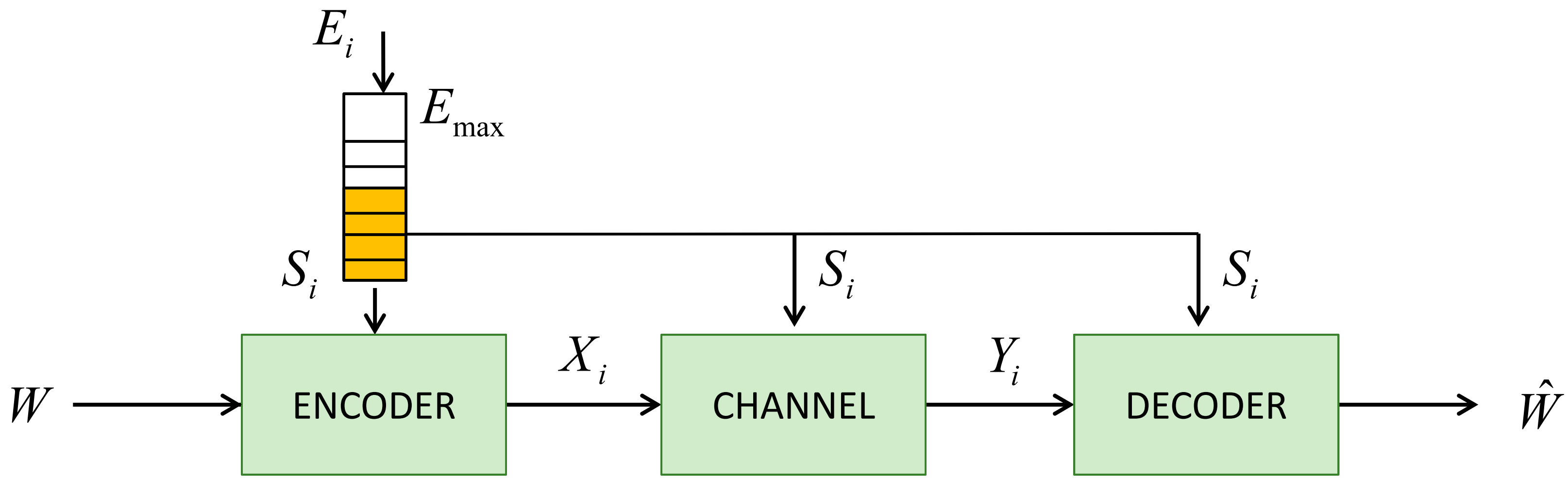
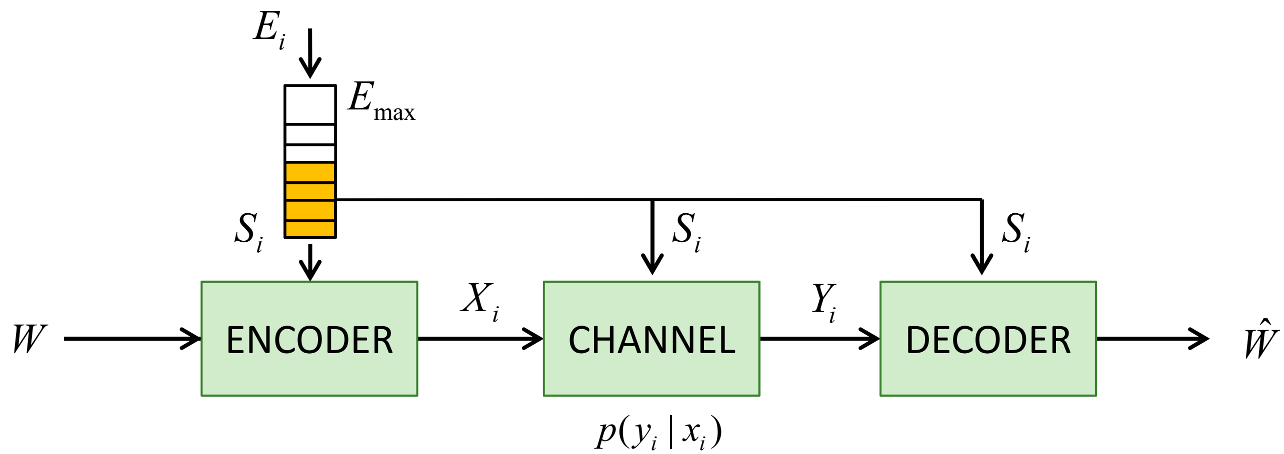
EH DMC with CSIT&CSIR [Ozel-Tutuncuoglu-Ulukus-Y.'14] (will be presented at ISIT 2014)



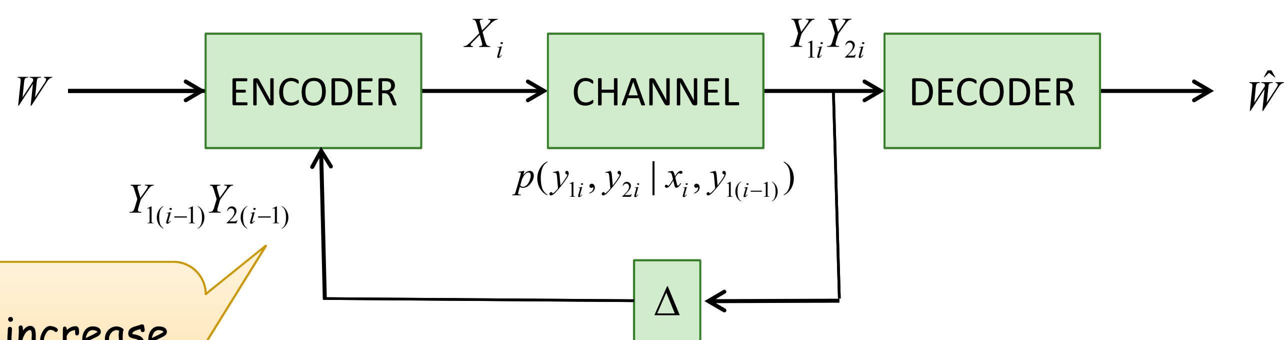
- The battery state S_i is available causally at both Tx and Rx
- Input symbol $X_i \in \{0,1,\ldots,K\}$, with $X_i \in k$ consuming k units of energy.
- **Information flows both through the physical channel and the battery state. (e.g., communication is possible without channel)**

EH DMC with CSIT&CSIR

Original EH channel with CSIT and CSIR:



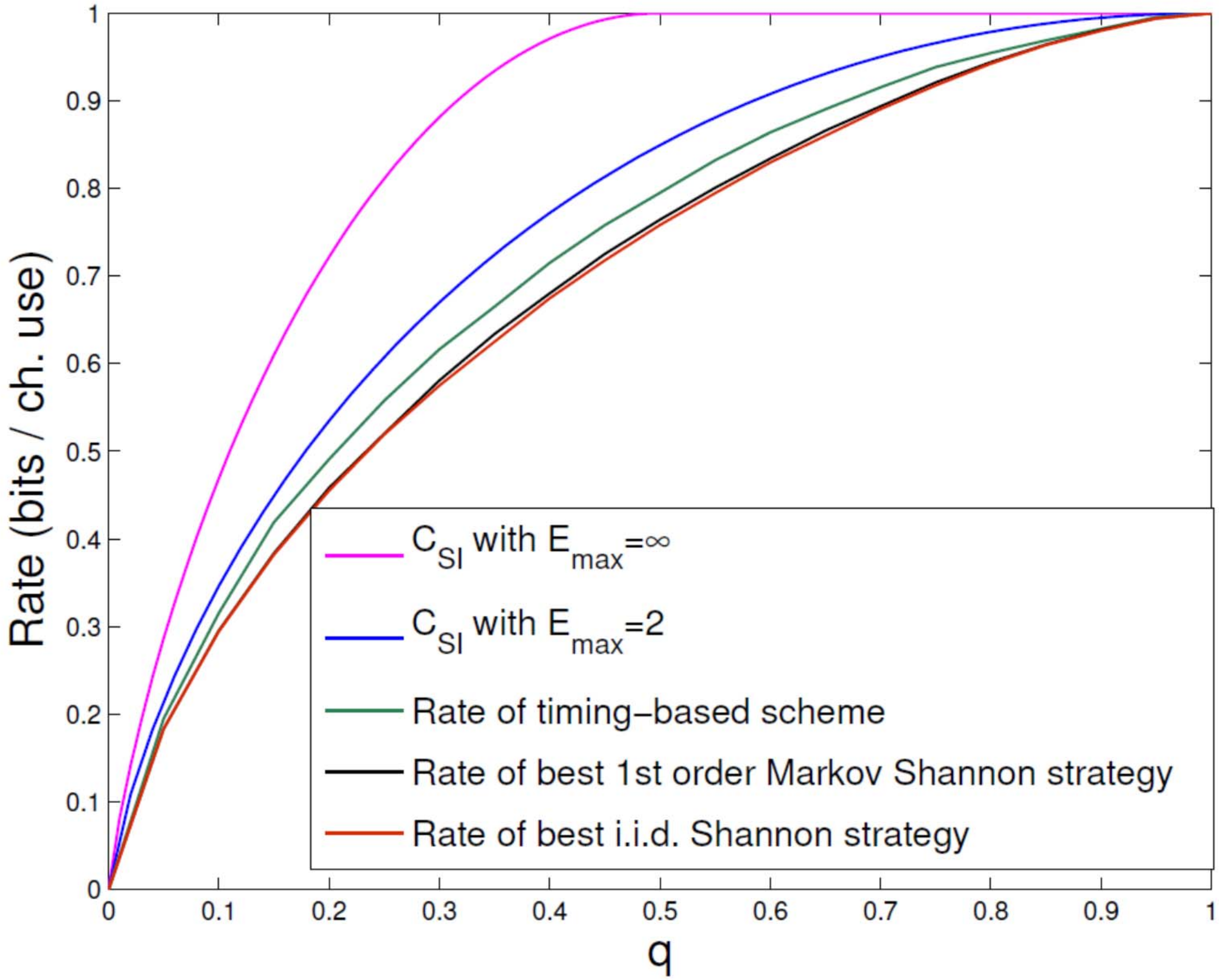
Equivalent channel with feedback: [Chen-Berger '05]



Feedback does not increase capacity

Weissman, Goldsmith 2009

EH DMC with CSIT&CSIR



Conclusion

- New networking paradigm: **energy harvesting nodes**
- New design insights arise from new energy constraints!
- Realistic concerns, e.g. storage capacity, storage efficiency impact transmission policies.
- Multi-terminal scenarios need to be handled with care.
- **Cooperation with an energy harvesting relay** or **energy cooperation** brings additional insights and possibilities.
- Information theoretic formulations are challenging but promising to yield new insights.

Current Studies and Open Problems

- Information theoretic limits, optimal coding schemes for energy harvesters
- Operational principles of energy harvesting receivers
- Impact of EH on signal processing PHY algorithms
- Impact on network protocols
- Efficient online schedules, simple practical implementations
- Papers: http://wcan.ee.psu.edu/