Foundations of Energy Harvesting and Energy Cooperating Wireless Communications

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Wireless Communications & Networking Laboratory
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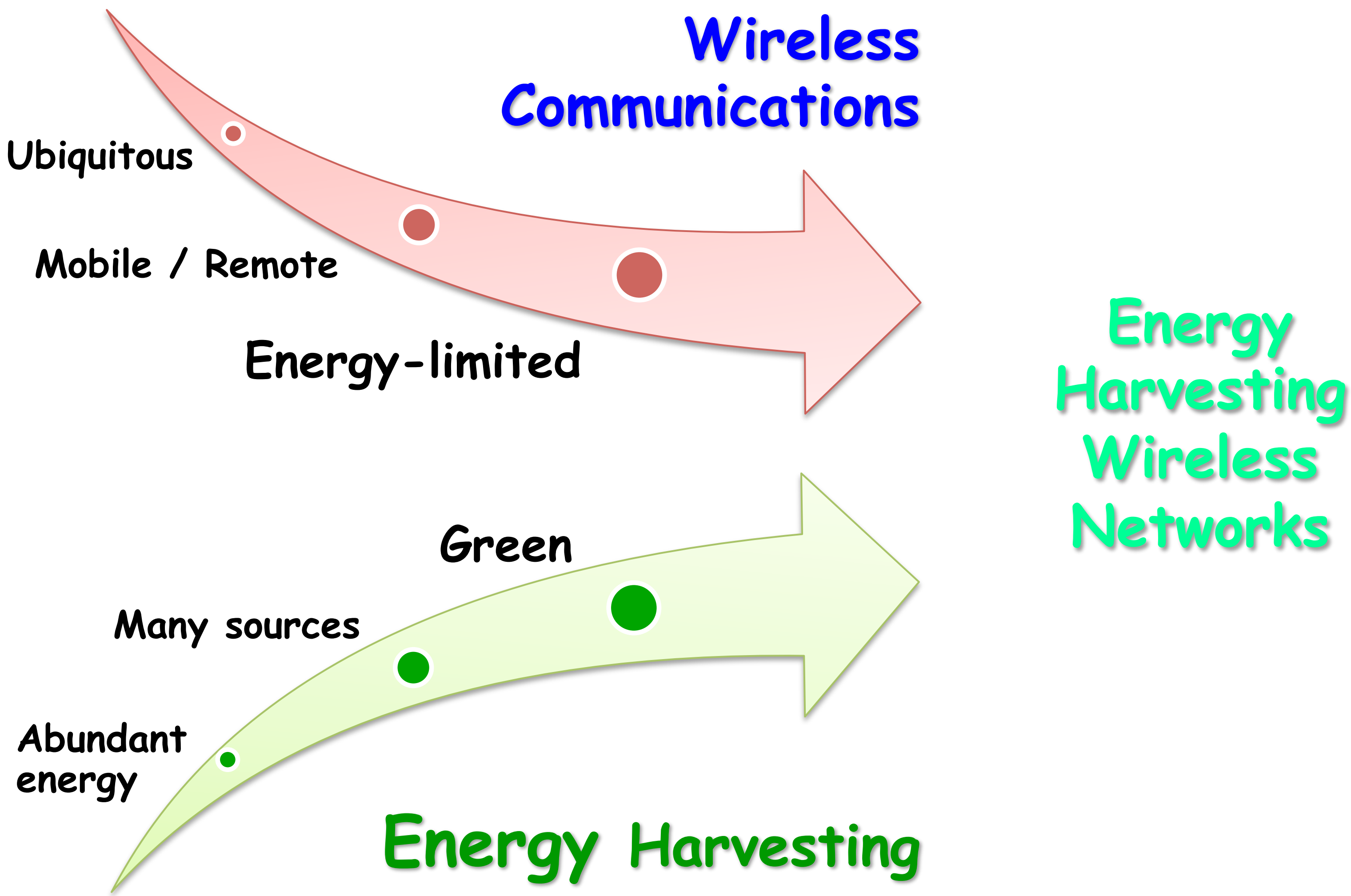
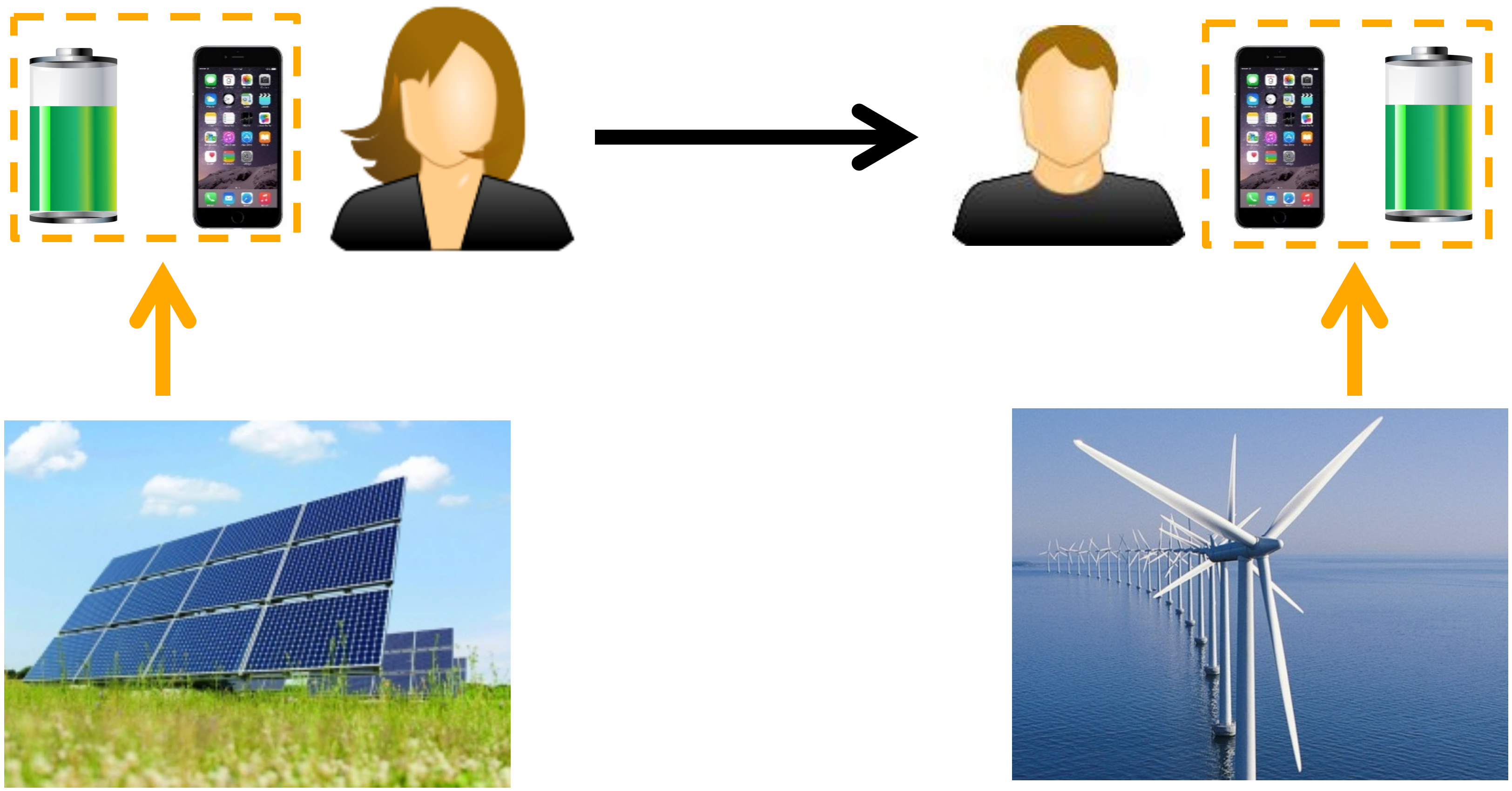
Introduction



Energy Harvesting Networks

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

What could EH bring to communications?



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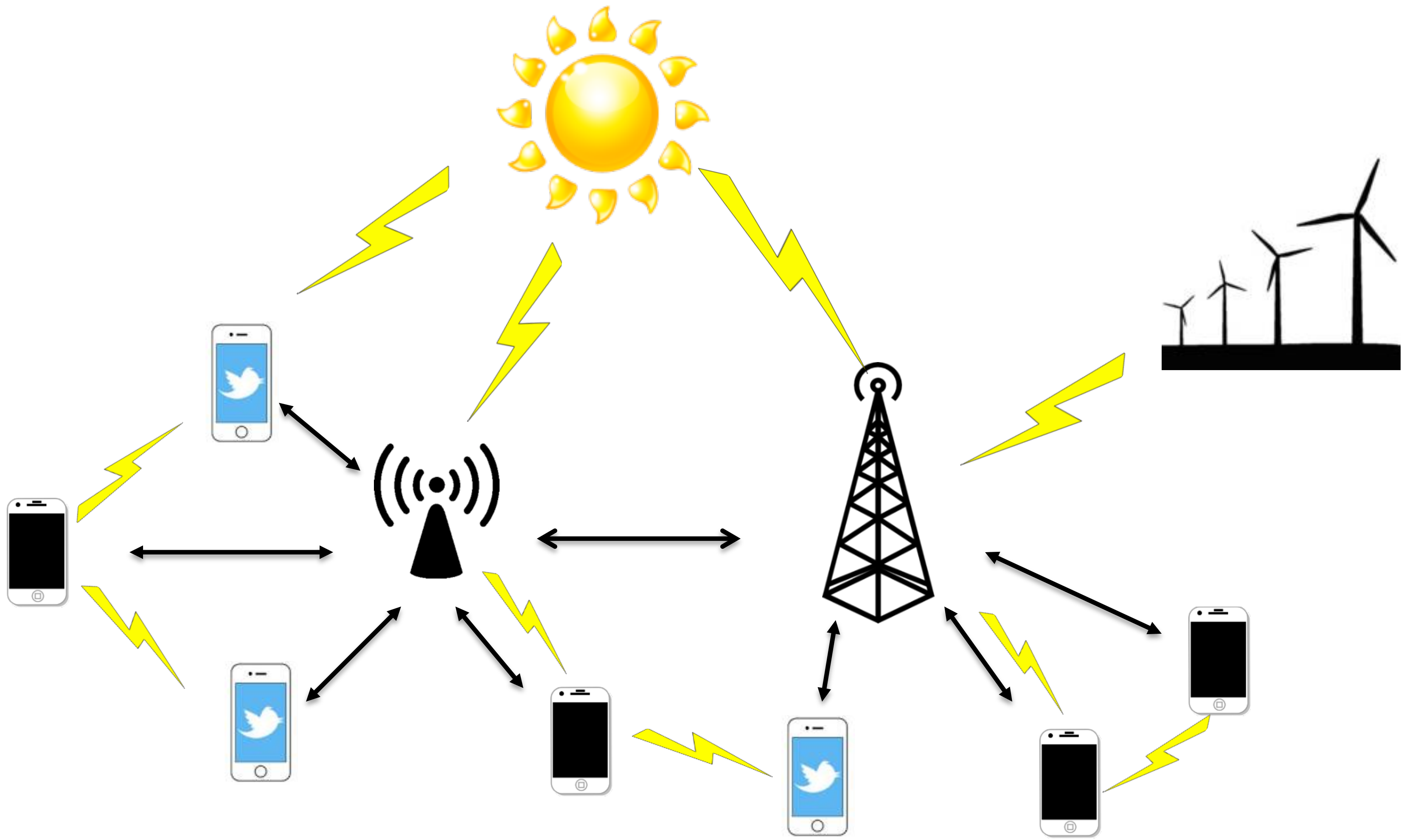
Wireless Energy Cooperation



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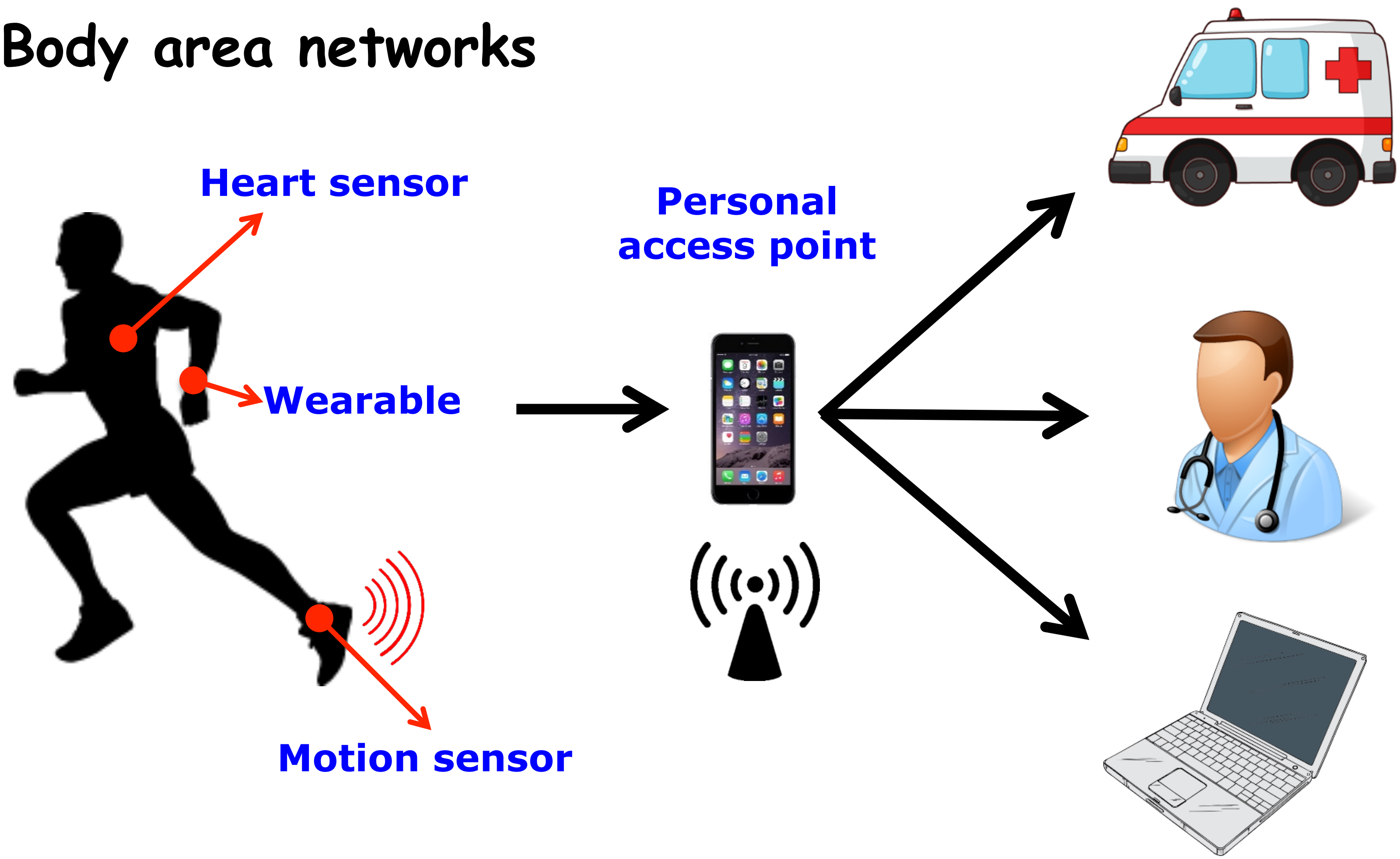
Energy Harvesting Applications

Body area networks



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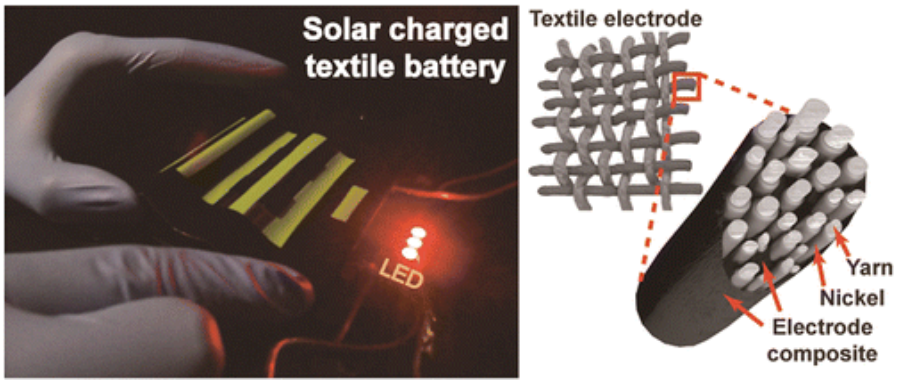
Energy Harvesting Applications



KAIST's Solar charged textile battery

MC10's **biostamps**

for medical monitoring,

powered **wirelessly**

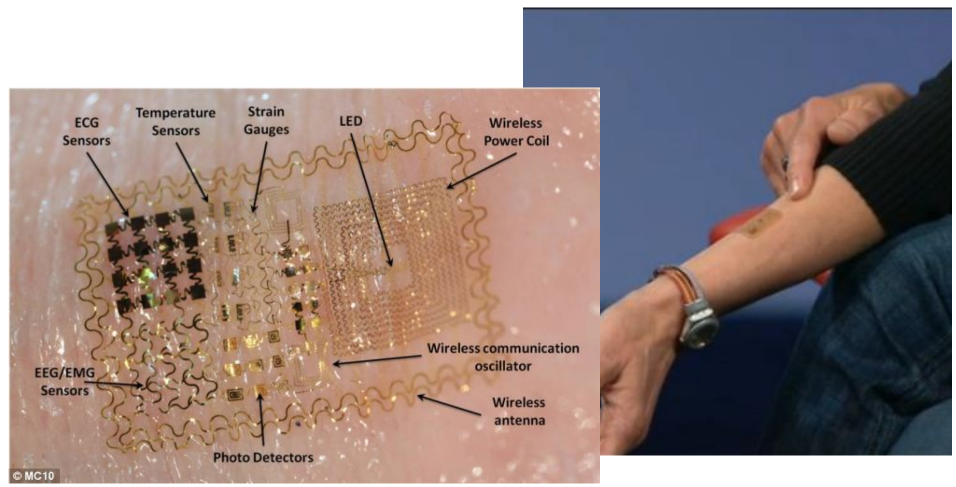
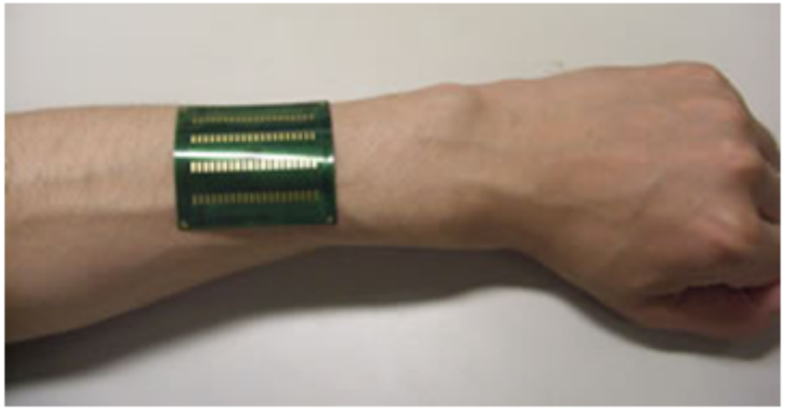
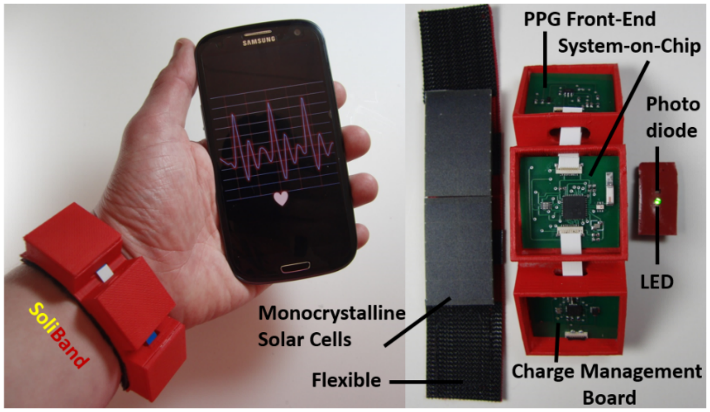


Image Credits: (top) http://pubs.acs.org/doi/abs/10.1021/nl403860k#aff1 (bottom)) http://www.dailymail.co.uk/sciencetech/article-2333203/Moto-X-Motorola-reveals-plans-ink-pills-replace-ALL-passwords.html

Energy Harvesting Applications

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

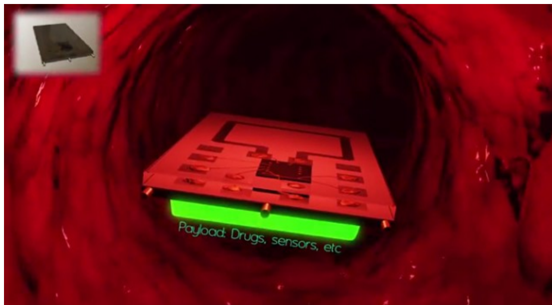




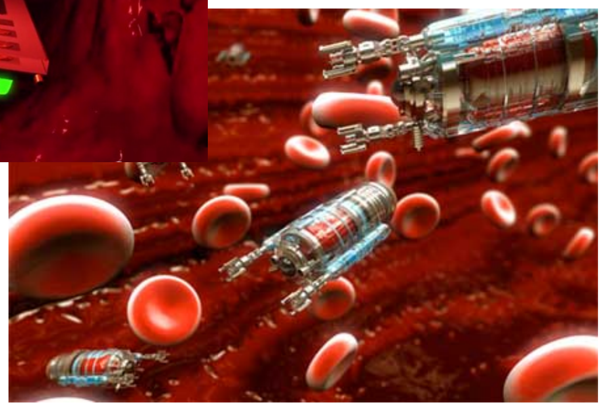
Health tracker utilizing **solar cells**

Image Credits: (top) http://www.fujitsu.com/global/news/pr/archives/month/2010/20101209-01.html
(bottom) https://assist.ncsu.edu/research/

Energy Harvesting Applications



In-body (intravascular) wireless devices



Proteus Biomedical pills,
powered by **stomach acids**

Image Credits: (top) http://www.extremetech.com/extreme/119477-stanford-creates-wireless-implantable-innerspace-medical-device
(middle) http://www.imedicalapps.com/2012/03/robotic-medical-devices-controlled-wireless-technology-nanotechnology/
(bottom) http://scitechdaily.com/smart-pills-will-track-patients-from-the-inside-out/

What is in it for us?

- New: communication theory of EH nodes
- New: information theory of EH nodes

Key new ingredient:

A **set of energy feasibility constraints** based on harvests govern the communication resources.

Communications

- **New Wireless Network Design Challenge:**
  A **set of energy feasibility constraints** based on harvests govern the communication resources.
- **Design question:**
  When and at what rate/power should a "rechargeable" (energy harvesting) node transmit?
- **Optimality? Throughput; Delivery Delay**
- **Outcome: Optimal Transmission Schedules**

Two main metrics

- **Short-Term Throughput Maximization (STTM):**

  Given a deadline, maximize the number of bits sent before the end of transmission.

- **Transmission Completion Time Minimization (TCTM):**

  Given a number of bits to send, minimize the time at which all bits have departed the transmitter.

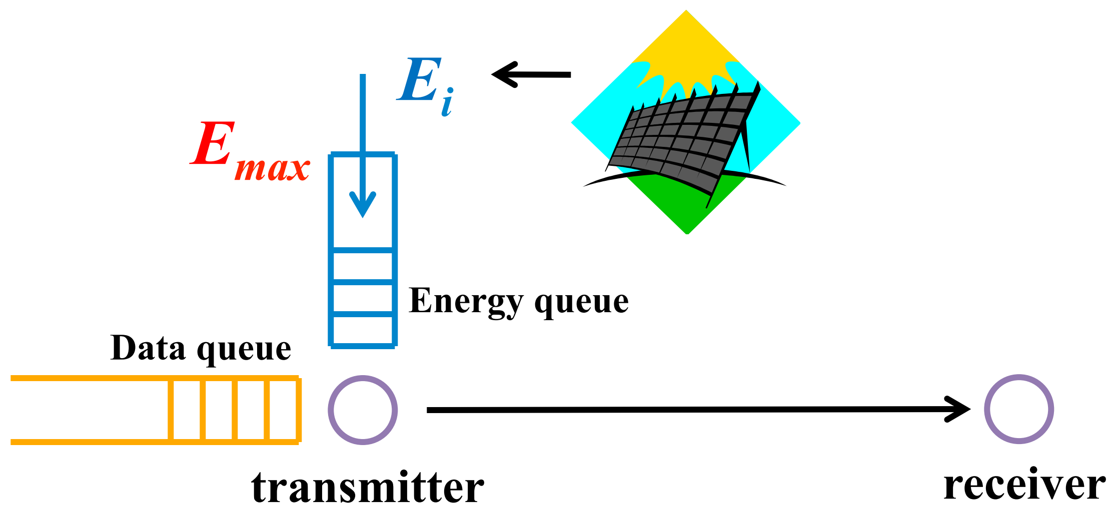
ST Throughput Maximization

[Tutuncuoglu-Y. 2012]

- 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

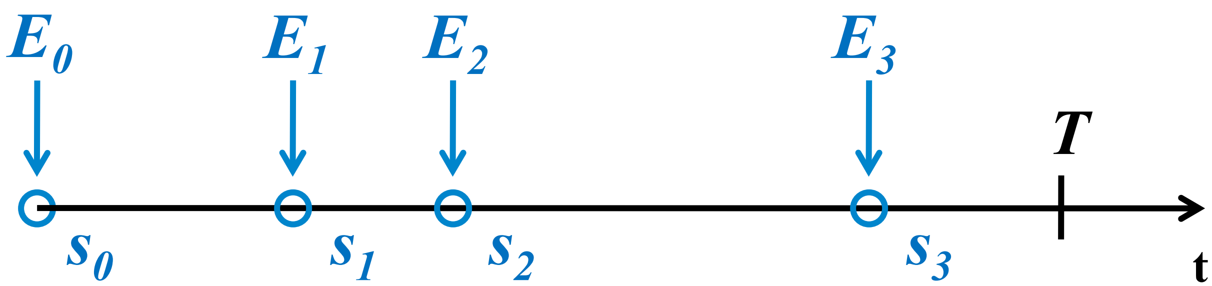
- Energy harvesting transmitter:



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

System Model

- Energy arrivals of energy E_i at times s_i



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

Power-Rate Function

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

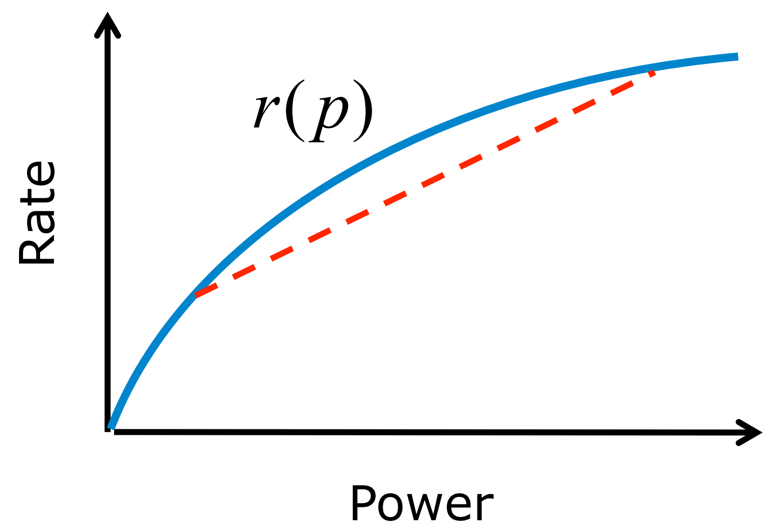
- **Assumptions on r(p):**

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

  ii. increases monotonically in p

  iii. strictly concave

  iv. $r(p)$ continuously differentiable



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

Notations and Assumptions

- Power allocation function: $p(t)$
- Energy consumed: $\int_0^T p(t)dt$
- Short-term throughput: $\int_0^T r(p(t))dt$

Concave rate in power →Given a fixed energy, a longer transmission with lower power departs more bits.

Energy Constraints

(Energy arrivals of E_i at times s_i)

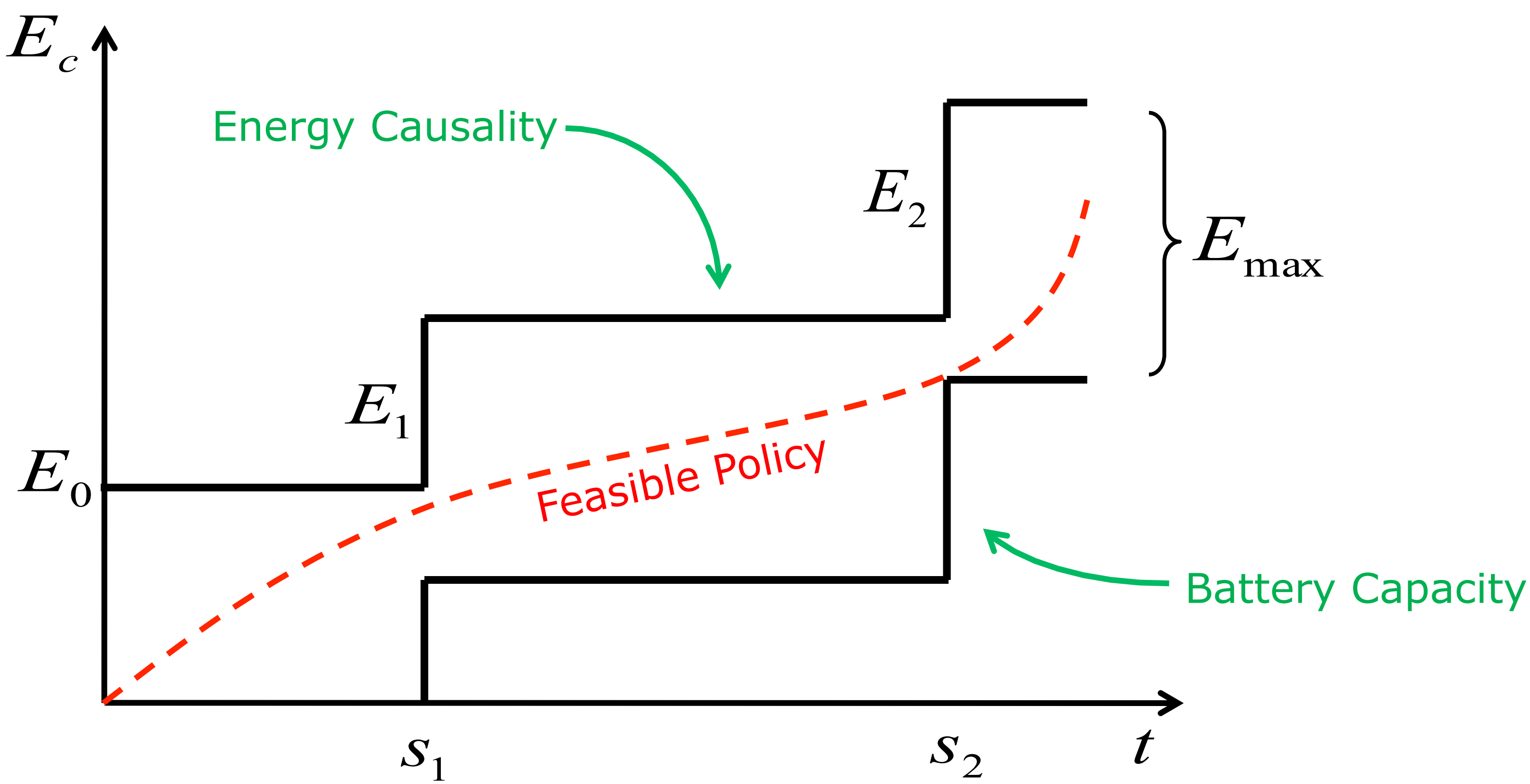
- **Energy Causality:** $\sum_{i=0}^{n-1} E_i - \int_0^{t'} p(t)dt \geq 0 \qquad s_{n-1} \leq t' \leq s_n$

- **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

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

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

- Convex constraint set, concave maximization problem

Necessary conditions for optimality of a transmission policy

- **Property 1:** Transmission power remains constant between energy arrivals.
- Let the total consumed energy in epoch $[s_i, s_{i+1}]$ be E_{total}

which is available at $t = s_i$. Then the power policy

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

is feasible and better than a variable power transmission; shown easily using concavity of $r(p)$

Necessary conditions for optimality

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

Proof:

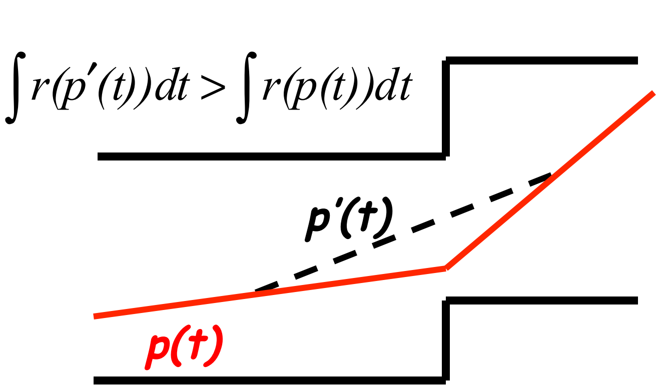
Assume an energy of Δ overflows at time τ

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

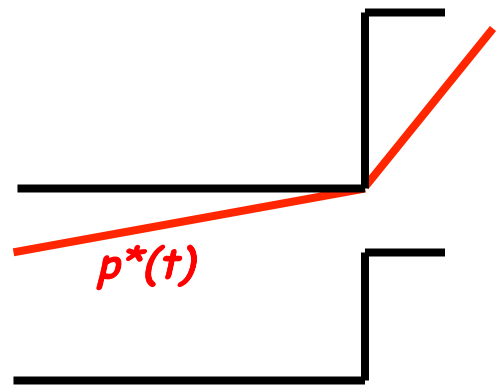
Then $\int_0^T r(p'(t))dt > \int_0^T r(p(t))dt$ since $r(p)$ is increasing in p

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



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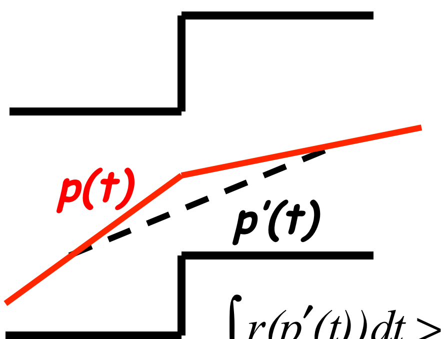
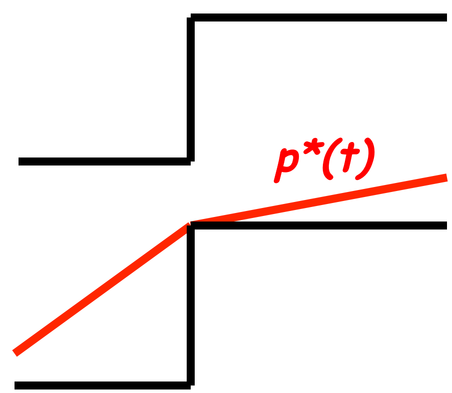


$$\int r(p'(t))dt > \int r(p(t))dt$$

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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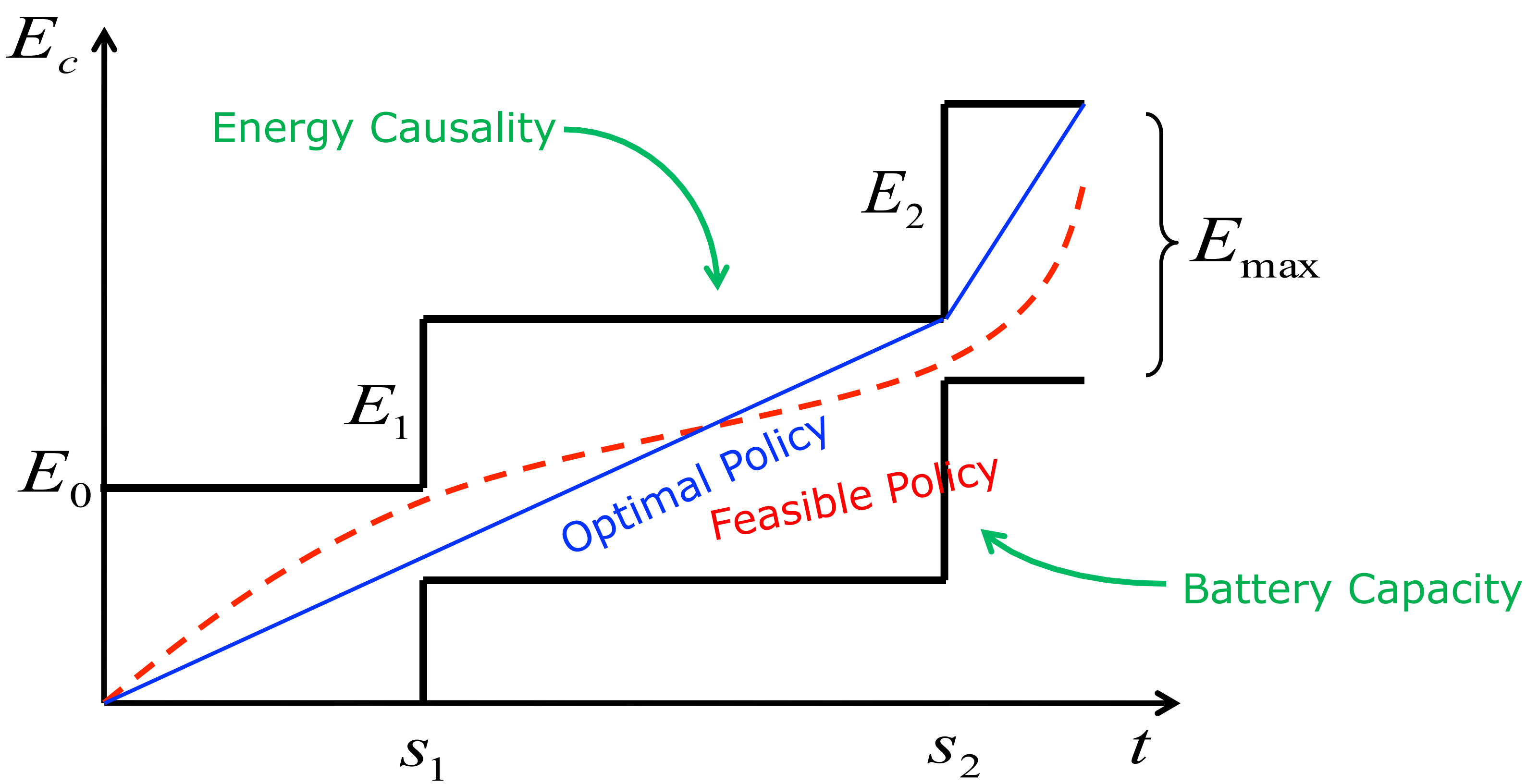
Implications of the properties [Tutuncuoglu-Y. 2012]

- **Structure of optimal policy is piece-wise linear.**

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

- For power to increase or decrease, policy must meet the upper or lower boundary of the tunnel respectively.
- At termination step, battery is depleted.
- Utilizing this structure, a recursive algorithm emerges to find the unique optimum policy [Tutuncuoglu-Y. 2012].

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:

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

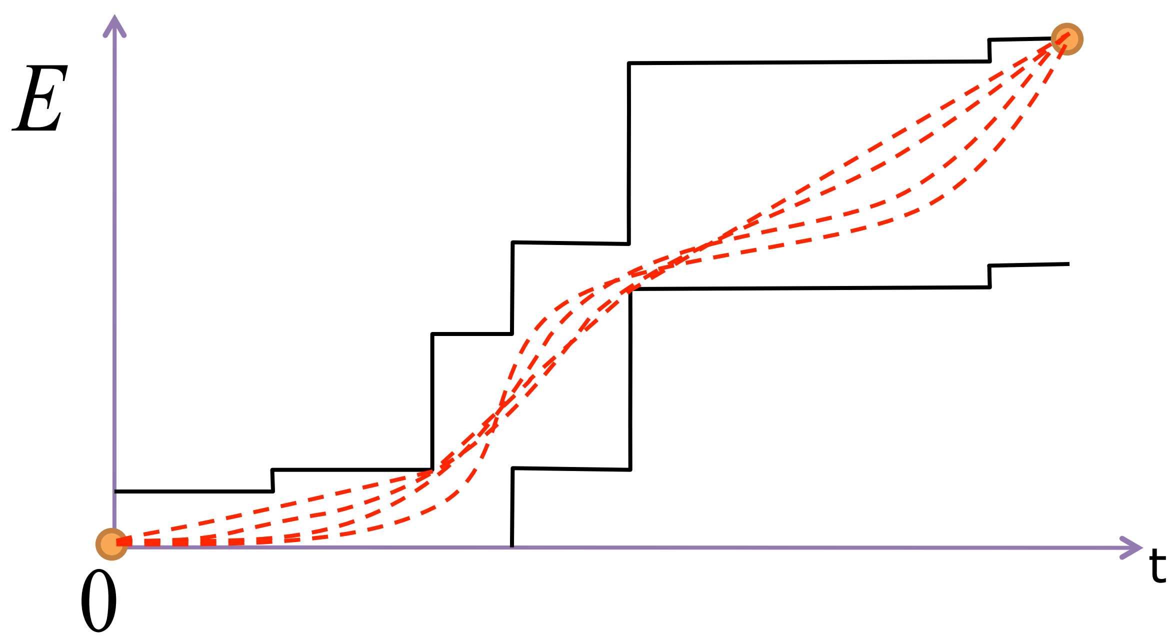
$$= \min_{p(t)} \underbrace{\int_0^T \sqrt{p^2(t)+1}\, dt}_{} \qquad s.t. \;\; p(t) \in \mathfrak{P}$$

length of policy path in energy tunnel

$\Rightarrow$ 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.

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Solution

- Complementary Slackness Conditions:

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

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

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

$$p_n^* = \left[\frac{1}{\sum_{j=n}^{N} (\lambda_j - \mu_j)} - 1 \right]^+$$

increases with positive λ_n
decreases with positive μ_n

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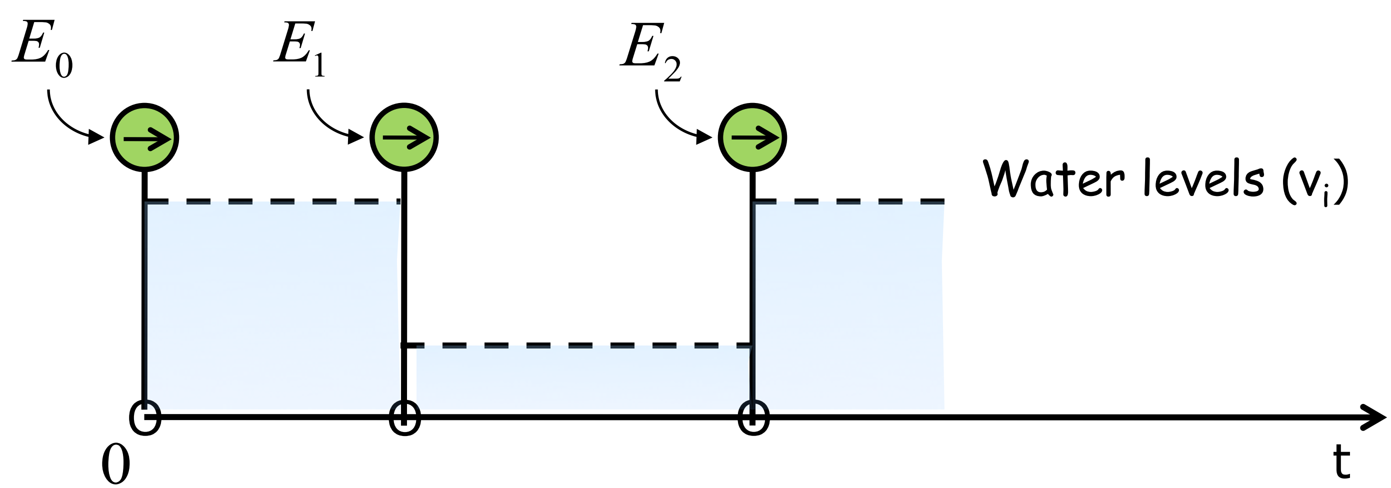
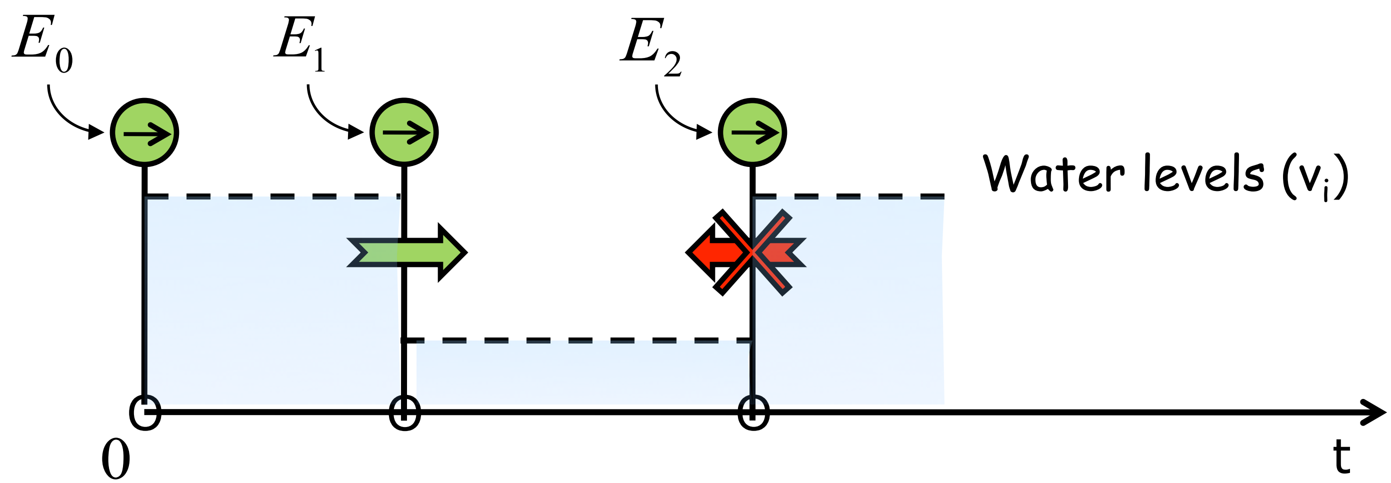
Directional Water-Filling

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



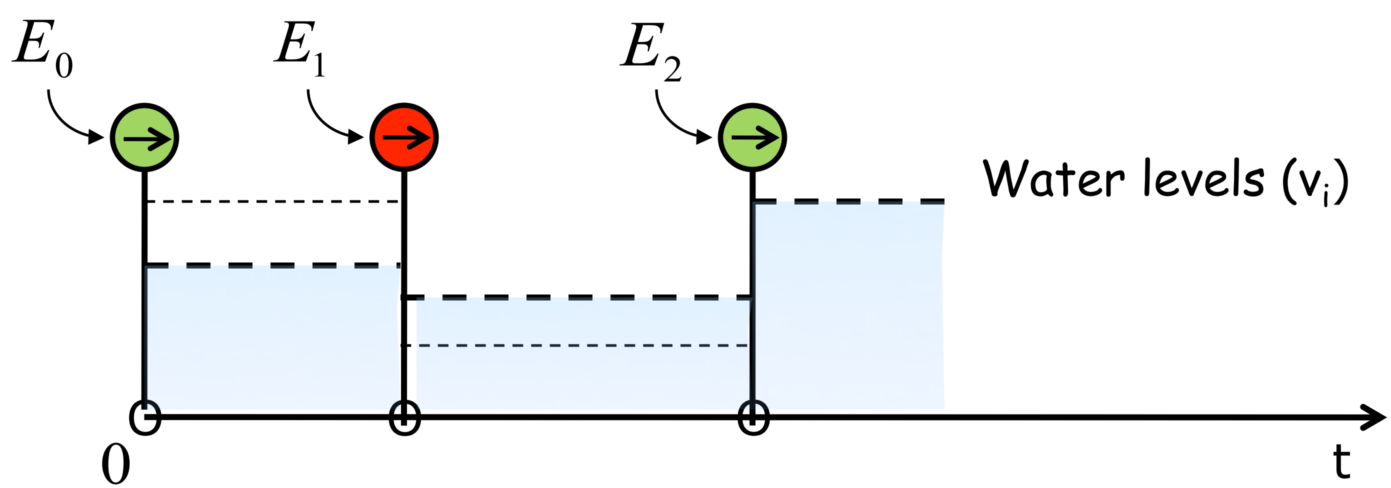
Directional Water-Filling

- 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



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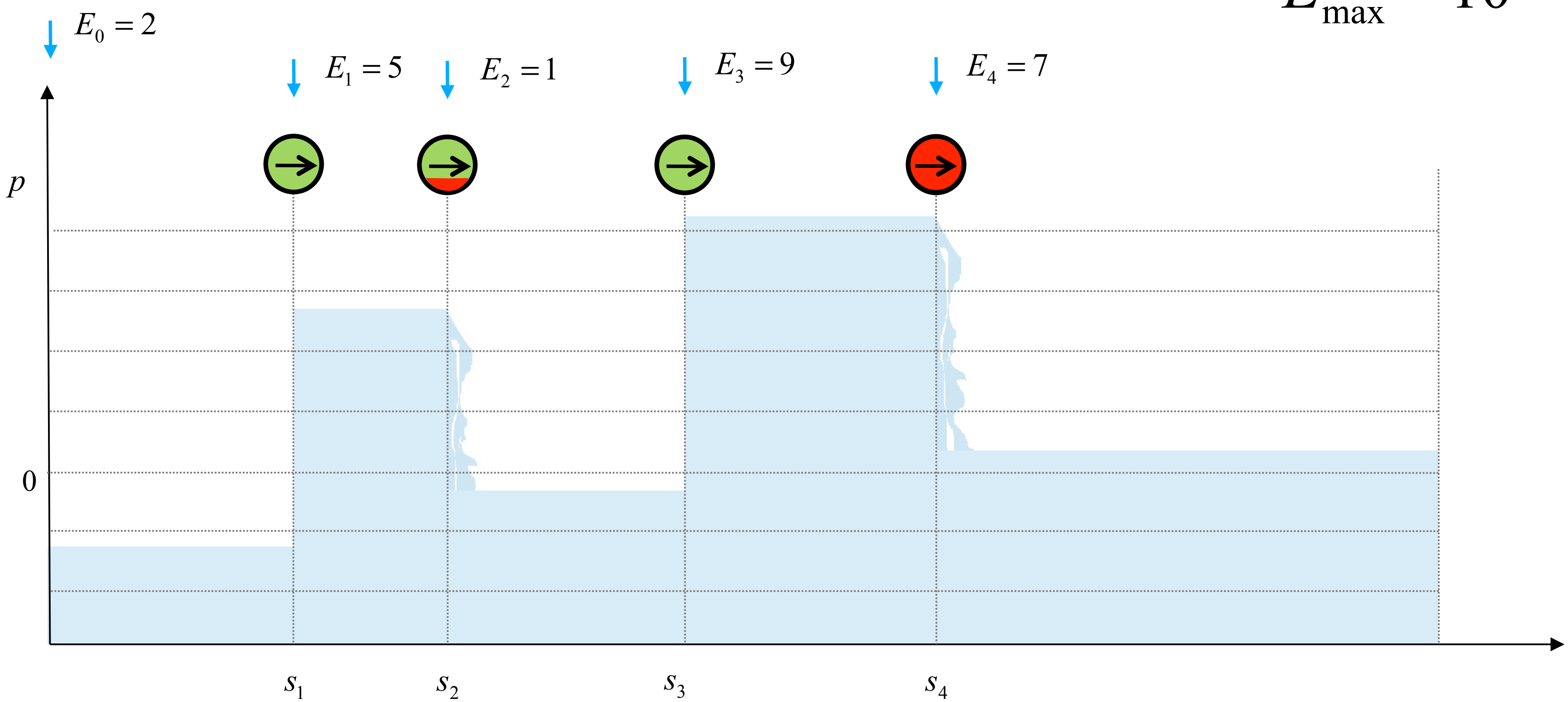
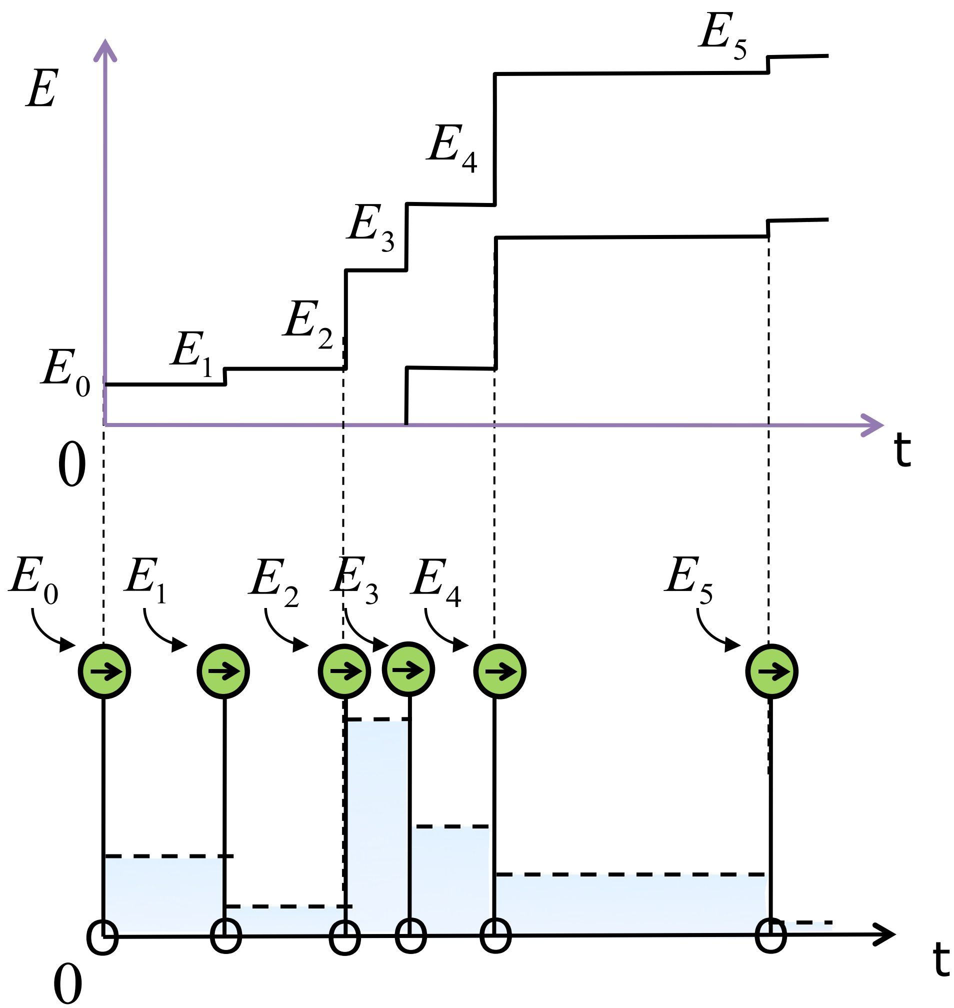
Example

$E_{max} = 10$

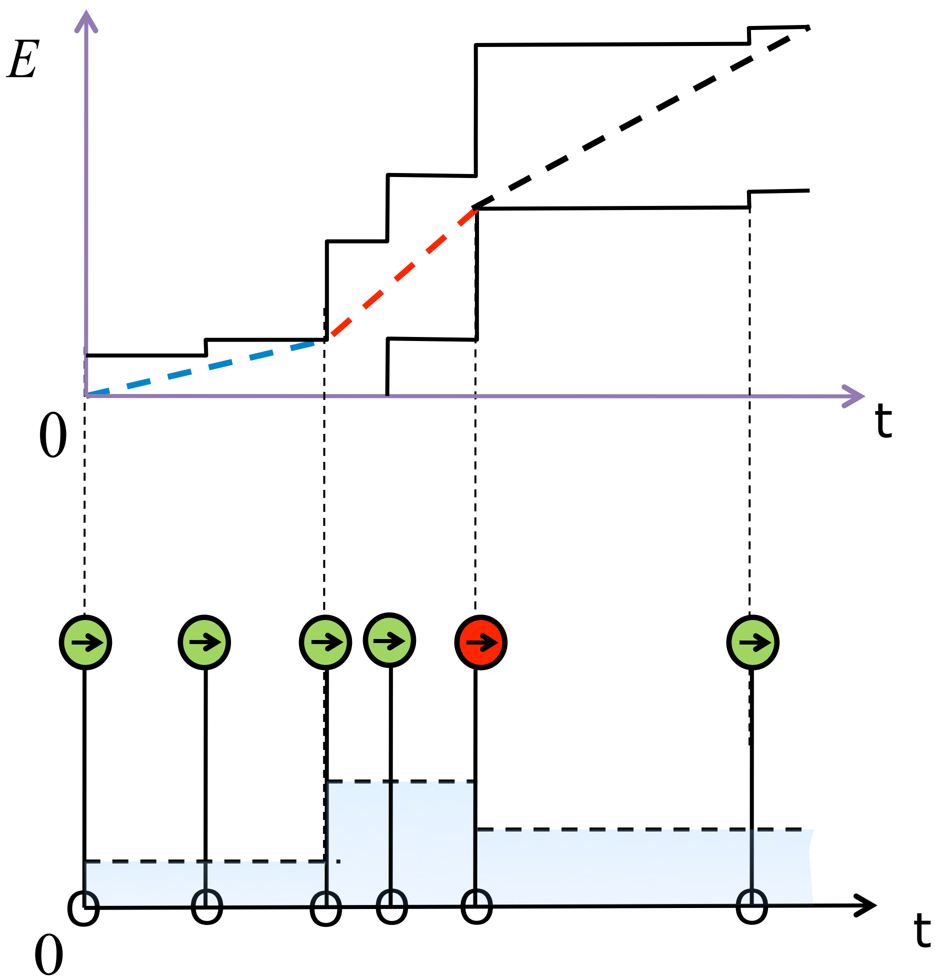


Directional Water-Filling



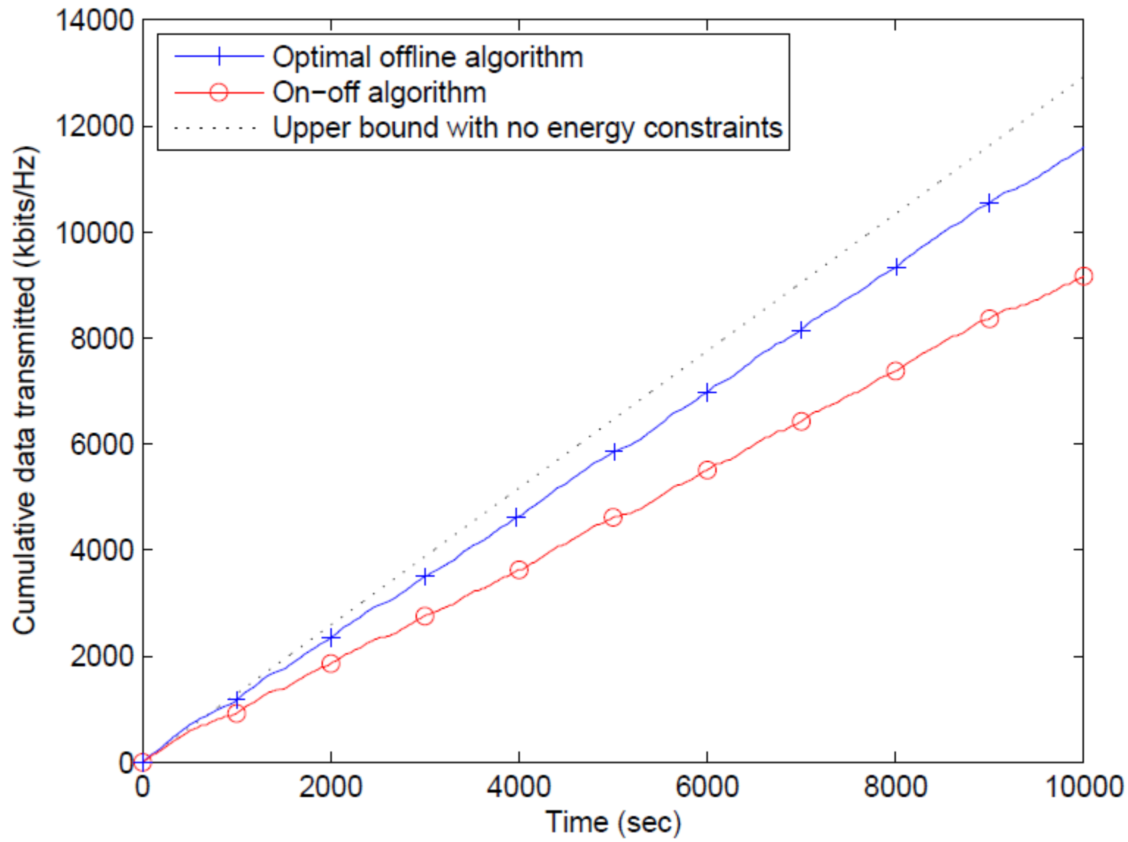
- Energy tunnel and directional water-filling approaches yield the same policy

Directional Water-Filling



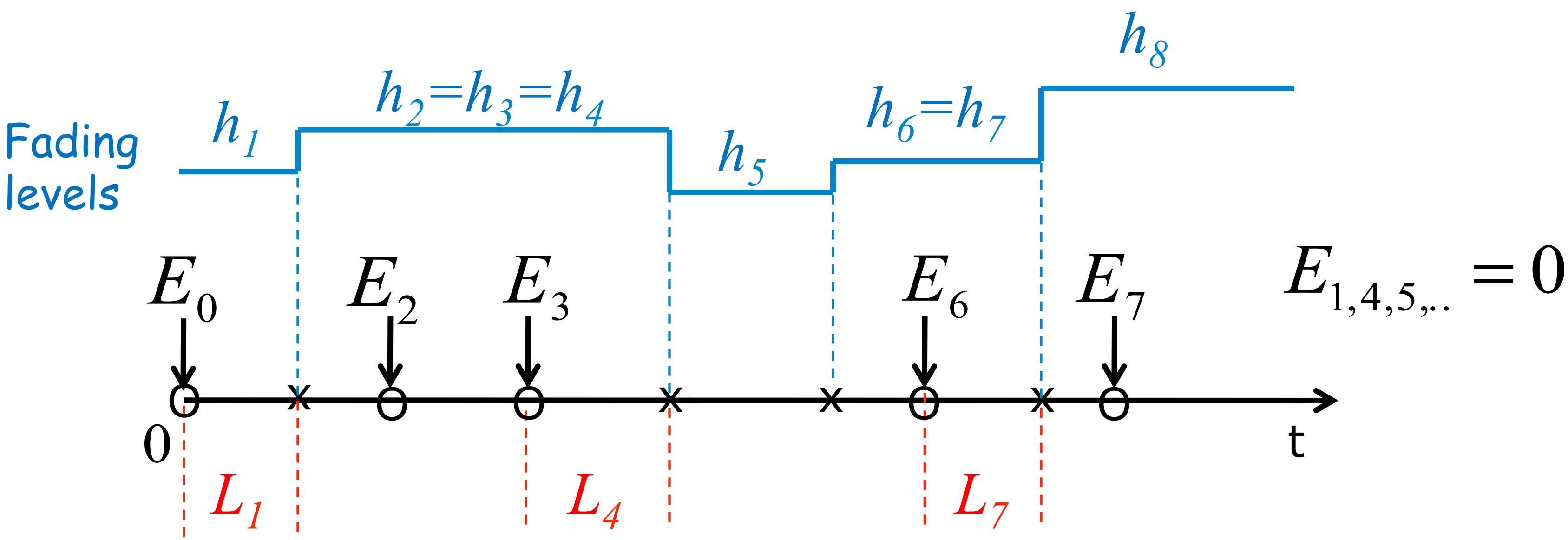
- Energy tunnel and directional water-filling approaches yield the same policy

Simulation Results



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

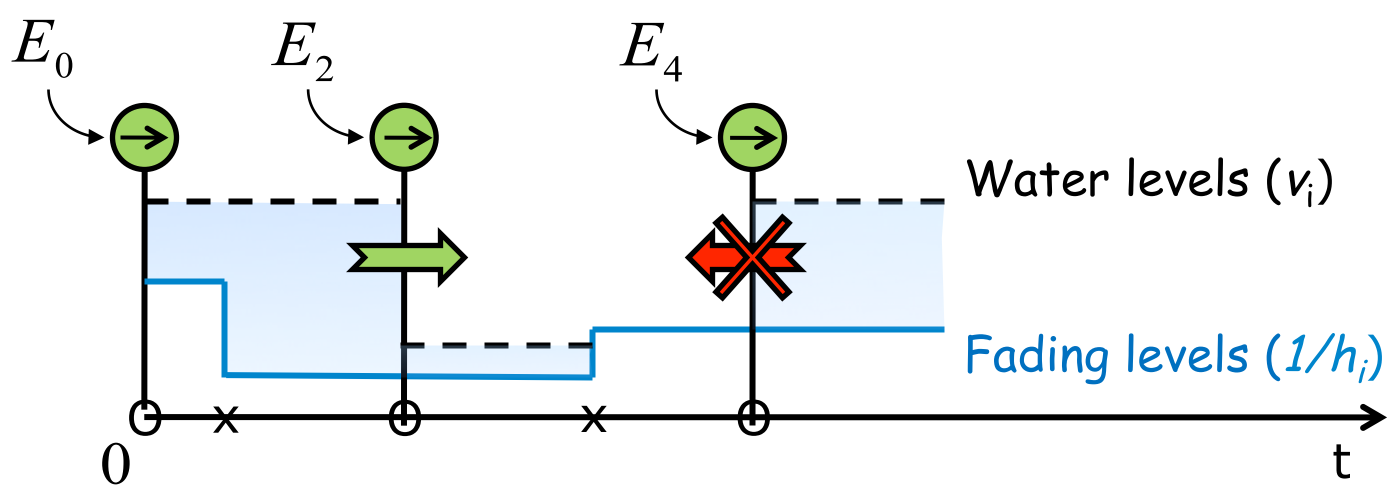
Fading Channels [Ozel-Tutuncuoglu-Ulukus-Y.'11]



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

Directional Water-Filling for Fading Channels

- Same directional water filling with base levels adjusted according to channel quality.
  - Directional water flow **(Energy causality)**
  - Limited water flow **(Battery capacity)**



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Transmission Completion Time Minimization (TCTM)

- Given the total number of bits to send as B, complete transmission in the shortest time possible.

$$\min_{p(t)} T \quad s.t. \quad B - \int_0^T r(p(t))dt \le 0, \;\; p(t) \in \mathfrak{P}$$

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

Relationship of STTM and TCTM

- Lagrangian dual of TCTM problem becomes:

$$\max_{u\geq 0}\left(\min_{p(t)\in\mathfrak{P}',T} T+u\left(B-\int_0^T r(p(t))dt\right)\right)$$

$$=\max_{u\geq 0}\left(\min_{T}\left(T+uB-u\cdot\max_{p(t)\in\mathfrak{P}}\int_0^T r(p(t))dt\right)\right)$$

STTM problem for deadline T

Relationship of STTM and TCTM

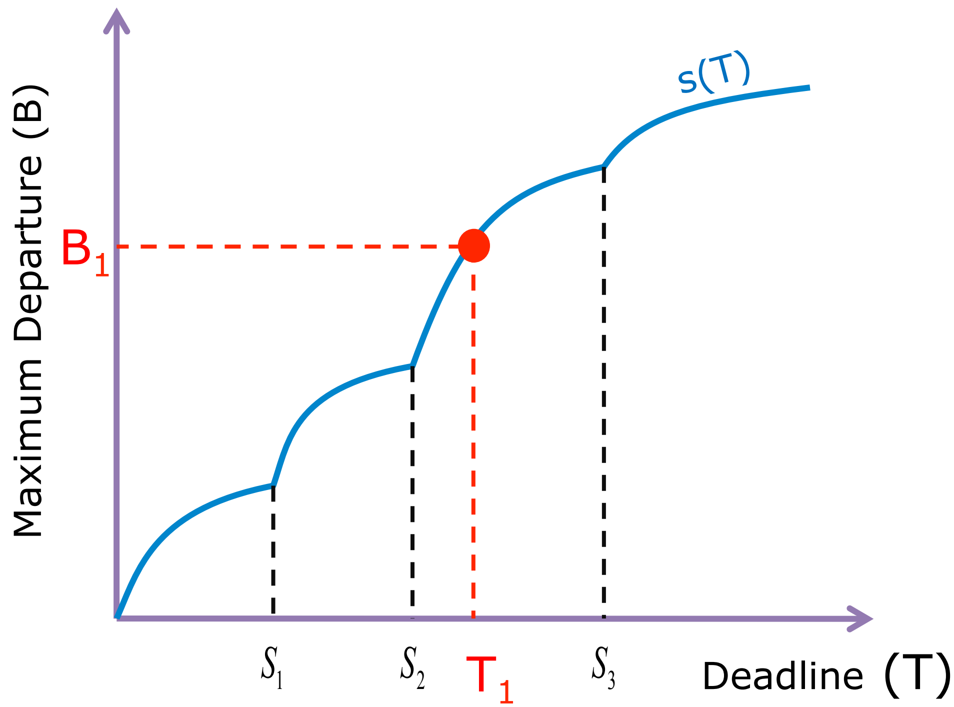
- Optimal allocations are identical:

STTM's solution for deadline T departing B bits $\equiv$ TCTM's solution for departing B bits in time T

- STTM solution can be used to solve the TCTM problem

Maximum Service Curve

- Continuous, monotone increasing, **invertible**



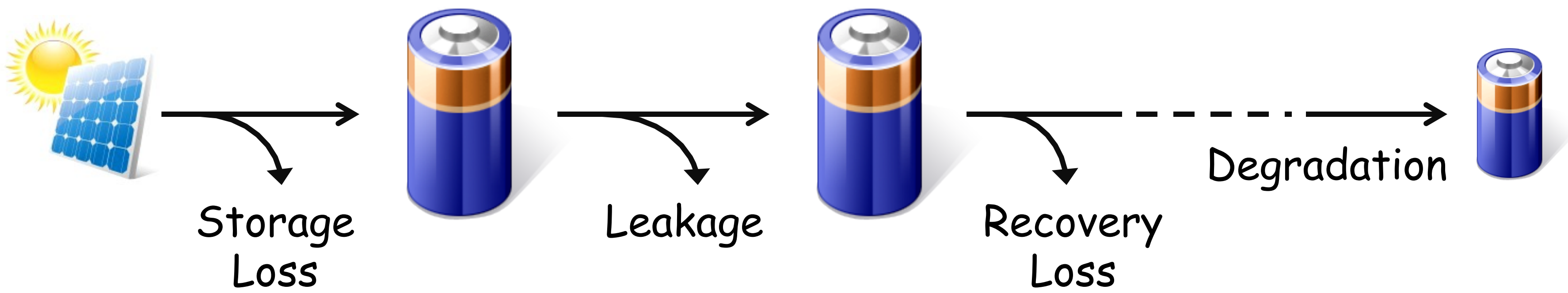
- Optimal allocation for TCTM with B_1 bits

=

Optimal allocation for STTM with deadline T_1

Transmission Policies with Inefficient Energy Storage

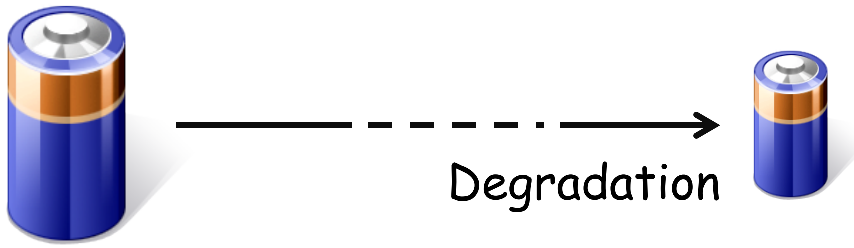
- Energy stored in a **battery**, **supercapacitor**, . . .
- **"Real life" issues:**



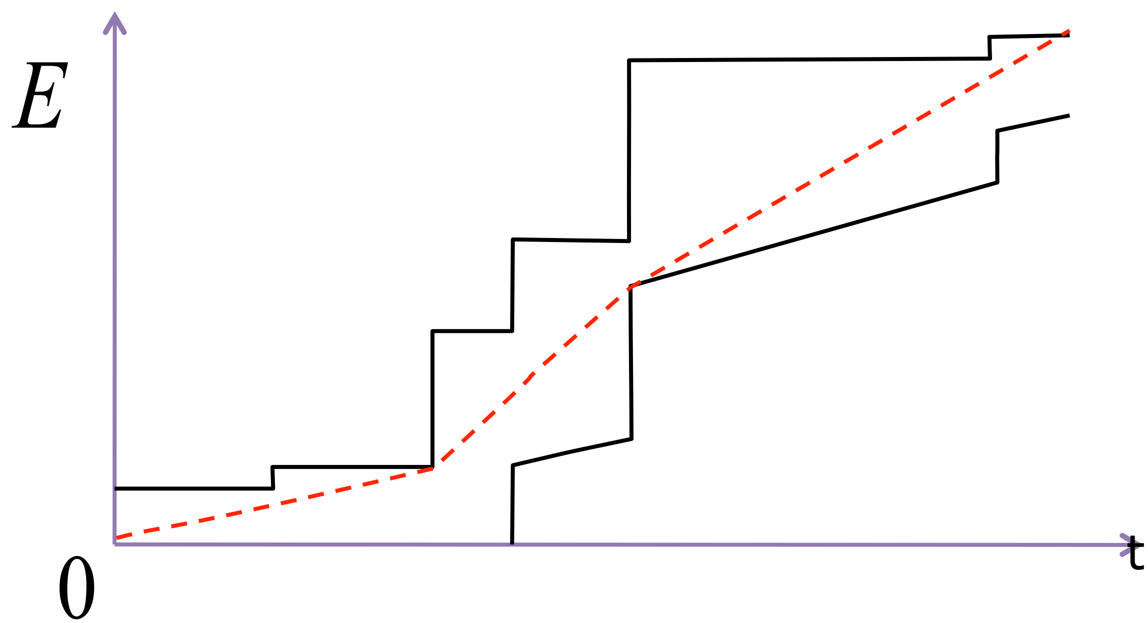
- [Devillers-Gunduz '12]: Leakage and Degradation
- [Tutuncuoglu-Y.-Ulukus '15]: Storage/Retrieval Losses

Battery Degradation

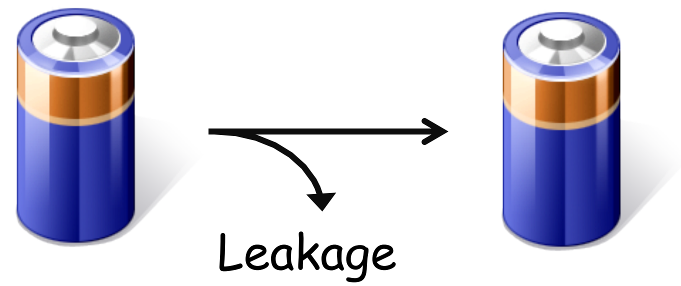
- [Devillers-Gunduz '12]



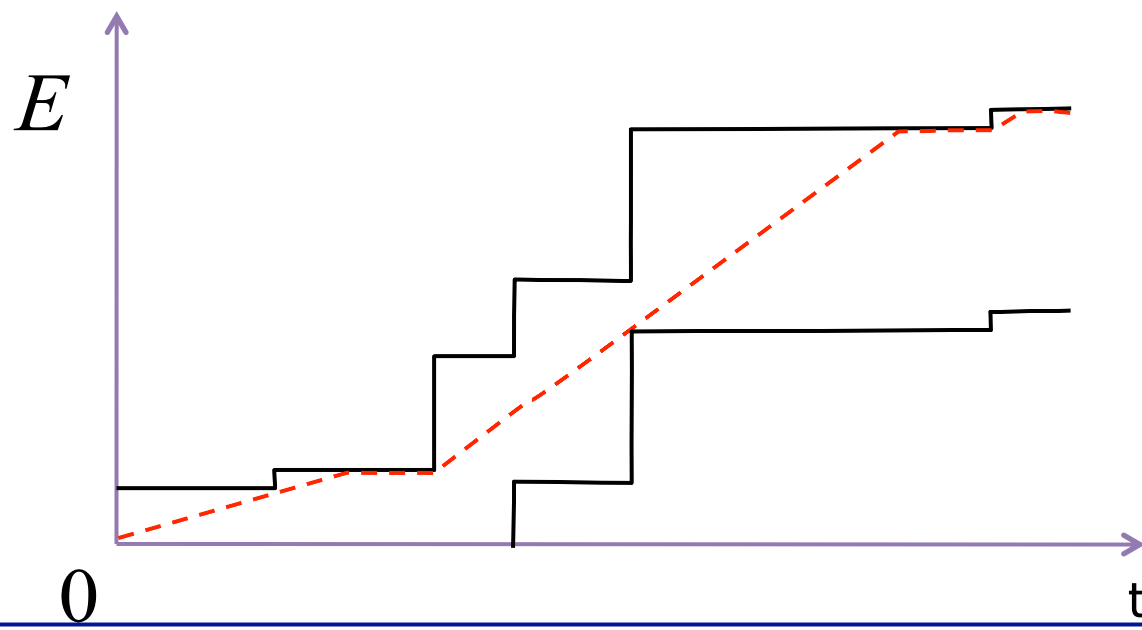
- **Optimal Policy:** Shortest path within **narrowing tunnel**



Battery Leakage

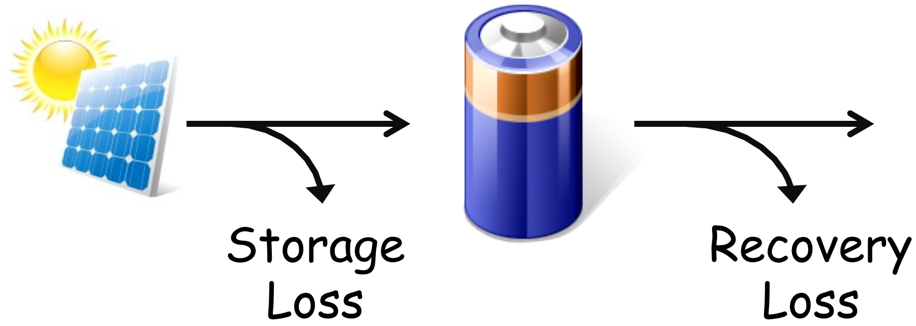


- [Devillers-Gunduz '12]
- **Optimal Policy:** When total energy in an epoch is low, deplete energy earlier to reduce leakage.



Storage/Recovery Losses

- [Tutuncuoglu-Y.-Ulukus '15]

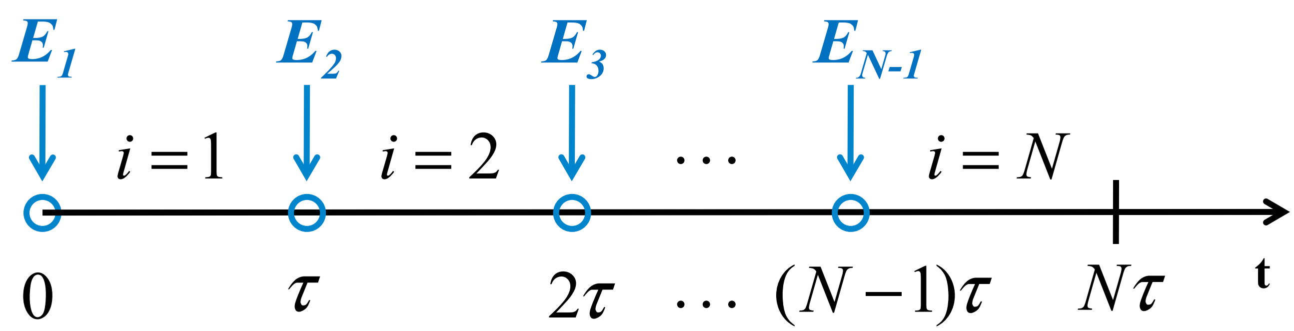


- **Main Tension:**

Concavity of r(p):
Use battery to maintain a constant power transmission

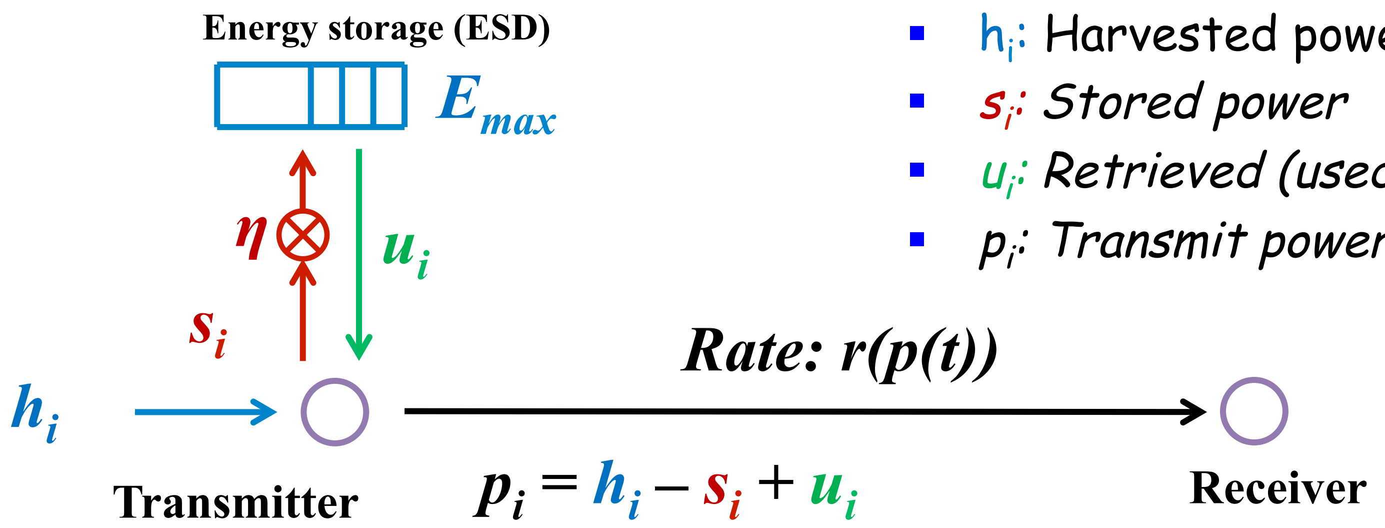
Battery inefficiency:
Storing energy in battery causes energy loss

Time slotted model



- **Time slots** of duration $\tau = 1\ s$
- **Energy harvests:** Size E_i at the beginning of time slot i

System Model



- h_i: Harvested power
- s_i: Stored power
- u_i: Retrieved (used) power
- p_i: Transmit power

- ESD has finite capacity E_{max} and storage efficiency η.
- **Energy Causality:** $$\sum_{n=1}^{i} \eta s_n - u_n \geq 0, \qquad i = 1, \ldots, N$$
- **Storage Capacity:** $$\sum_{n=1}^{i} \eta s_n - u_n \leq E_{\max}, \qquad i = 1, \ldots, N$$

Throughput Maximization

- Find optimal energy storage policy that maximizes the average throughput of an energy harvesting transmitter within a deadline of N time slots.

$$\max_{\{s_i, r_i\}} \sum_{i=1}^{N} r(E_i - s_i + u_i)$$

$$s.t.\quad 0 \le E_0 + \sum_{n=1}^{i} (\eta s_i - u_i) \le E_{\max}, \qquad i = 1, \ldots, N,$$

$$E_i - s_i + u_i \ge 0,\ s_i \ge 0,\ u_i \ge 0, \qquad i = 1, \ldots, N.$$

Throughput Maximization

$$\max_{\{s_i,r_i\}} \sum_{i=1}^{N} r(E_i - s_i + u_i)$$

$$s.t.\quad 0 \le \sum_{n=1}^{i} (\eta s_i - u_i) \le E_{\max}, \qquad i = 1,\ldots,N,$$

$$E_i - s_i + u_i \ge 0,\ s_i \ge 0,\ u_i \ge 0, \qquad i = 1,\ldots,N.$$

Old problem:

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

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

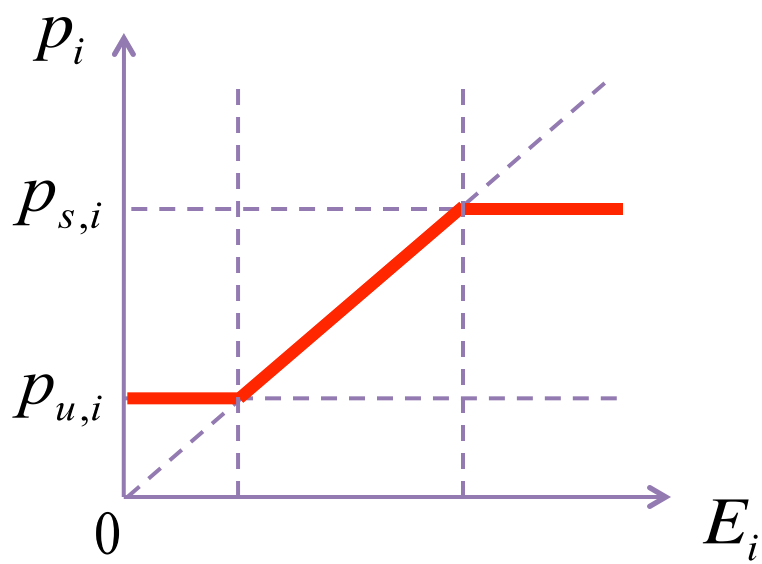
$$p_i \ge 0, \qquad i = 1,\ldots,N.$$

Optimal Power Policy

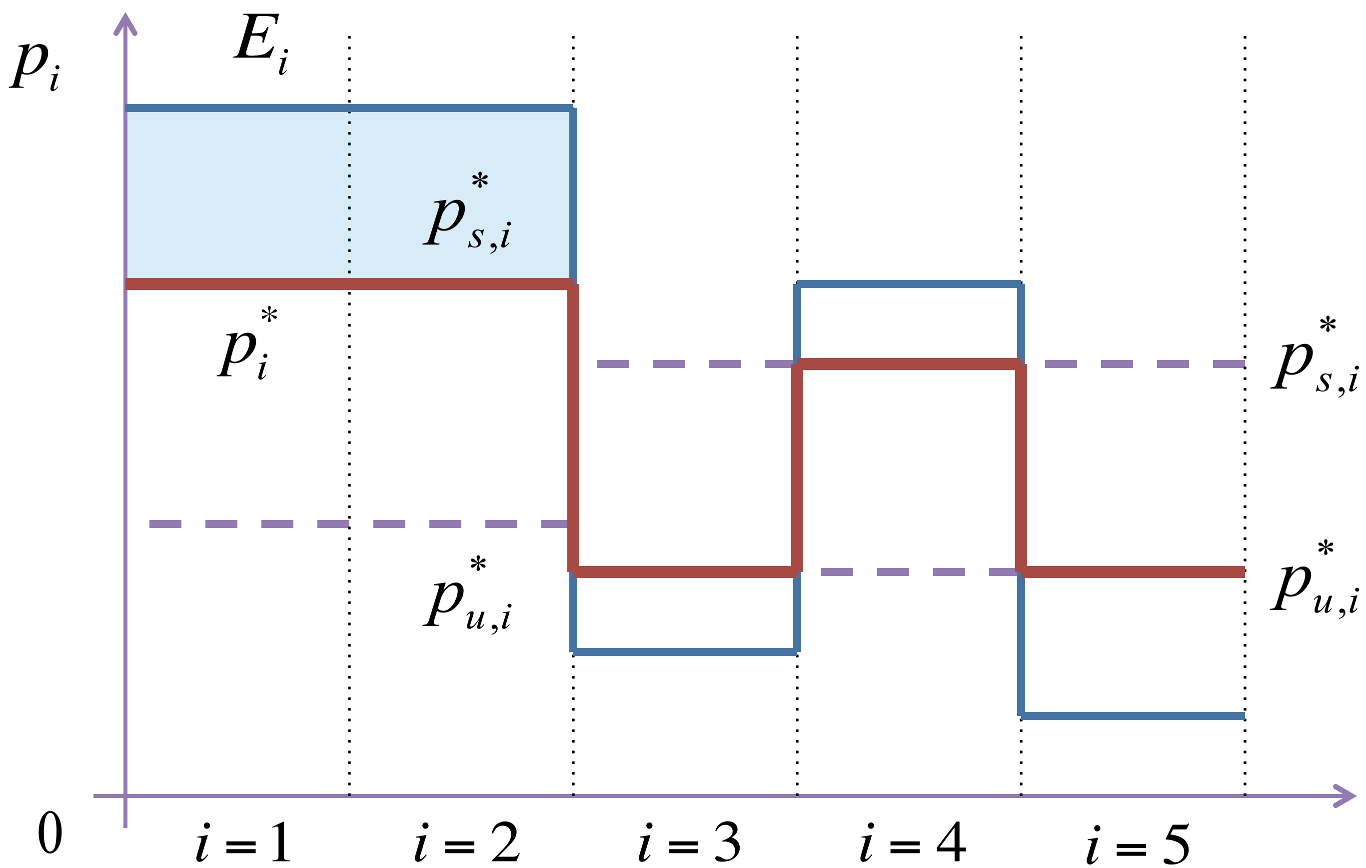
- **Structure of optimal policy:**

$$p_i = \begin{cases} [p_{s,i}]^+ & E_i \ge p_{s,i} \\ E_i & p_{u,i} \le E_i \le p_{s,i} \\ p_{u,i} & E_i \le p_{u,i} \end{cases}$$

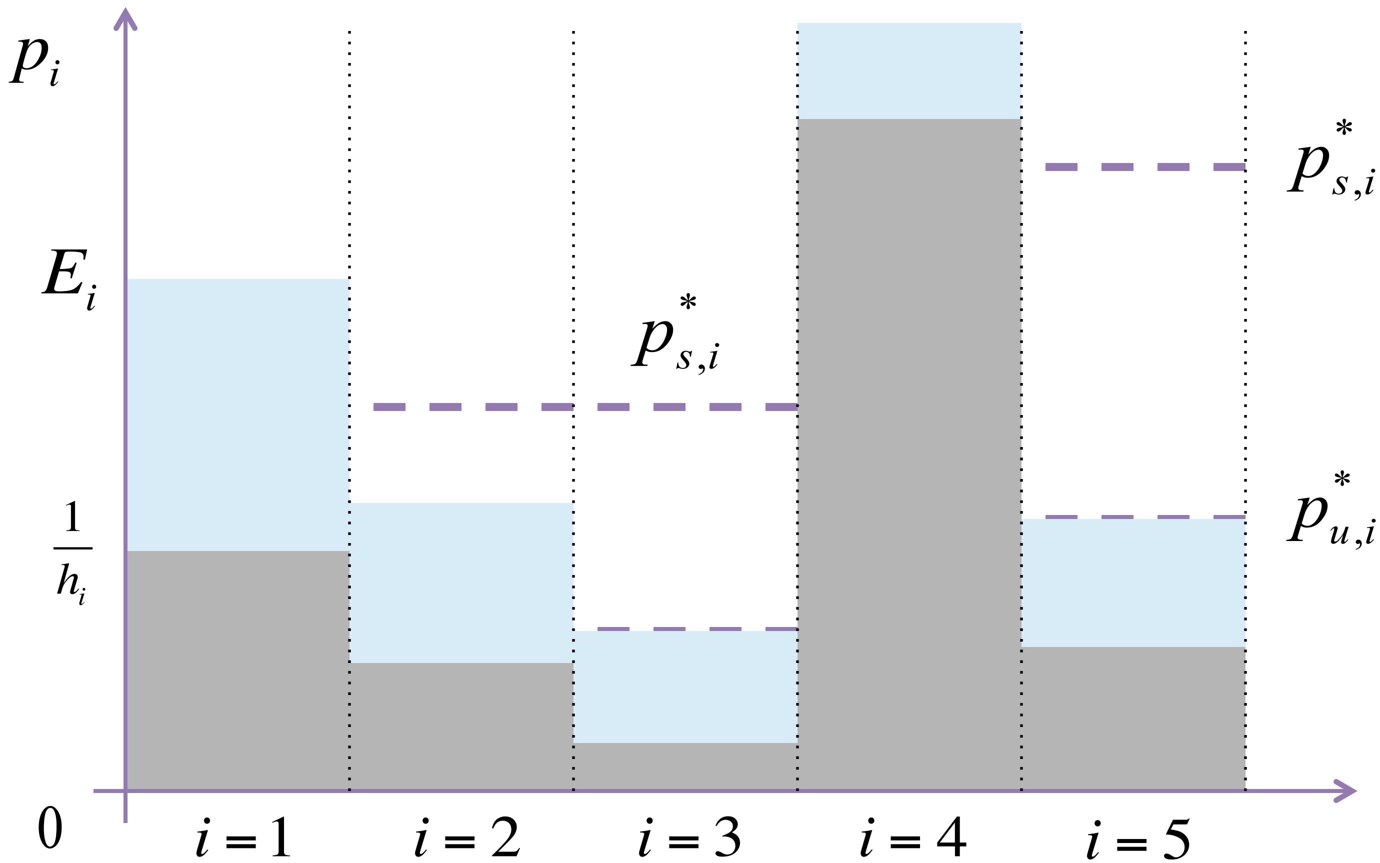
"Double Threshold Policy"



Optimal Power Policy



Optimal Power Policy
(Fading channel)

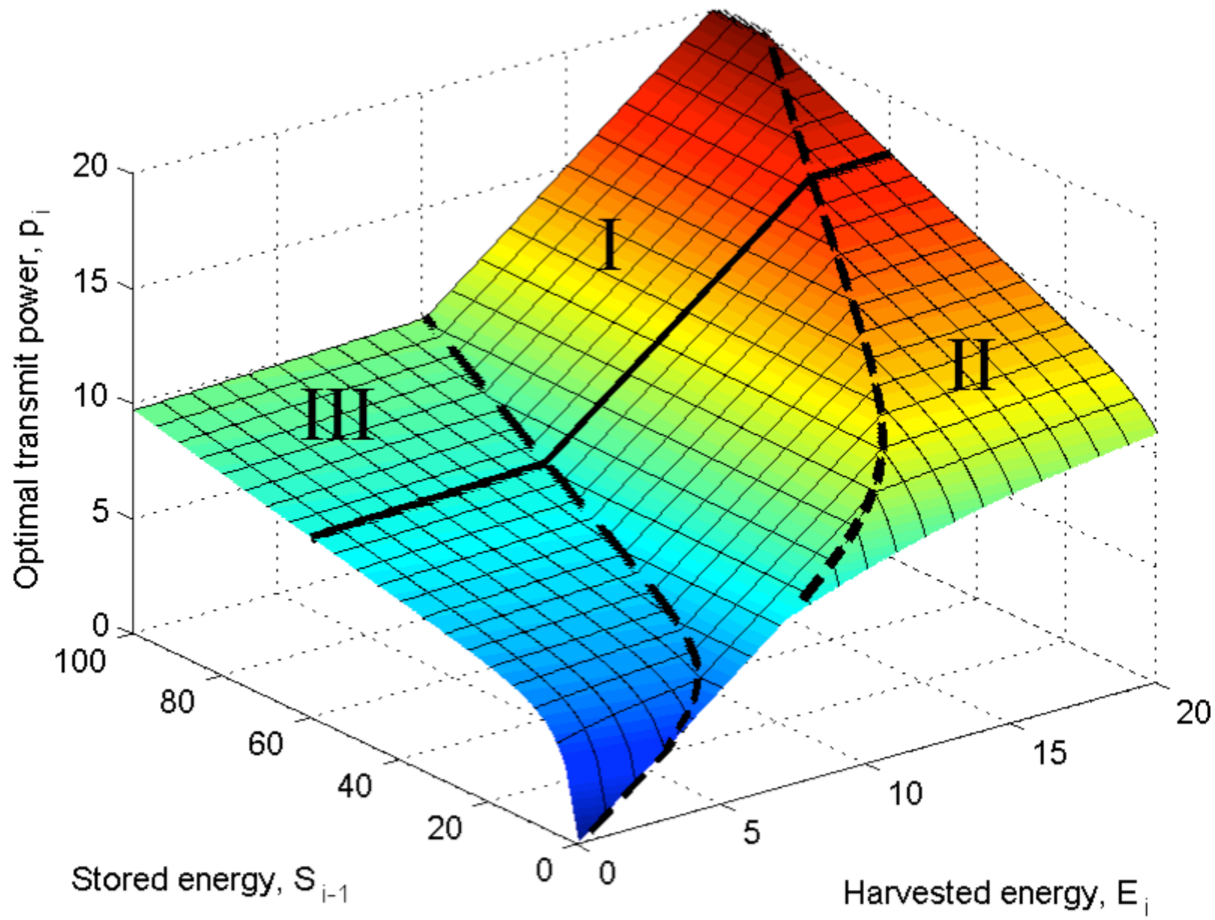


Optimal Online Policy

- So far, we have discussed **offline** policies.
- Energy harvesting scenario may not be predictable, or may not be available prior to transmission
- Markov Decision Process (MDP) formulation:
  - Action: $p_i = g_i(E^i, h^i)$
  - Value: $J_i(E^i, h^i) = \max_{\pi_i} r\left(g_i(E^i, h^i), h_i\right) + \mathbf{E}\left[\sum_{n=i+1}^{N} r\left(g_i(E^i, h^i), h_i\right)\right]$

$$= \max_{\pi_i} r\left(g_i(E^i, h^i), h_i\right) + \mathbf{E}\left[J_{i+1}(E^{i+1}, h^{i+1})\right]$$

Optimal Online Policy



Proposed Online Policy

- Both offline and online policies point to **thresholds**
- Choose **fixed thresholds** throughout transmission

$$p_i = \begin{cases} \max\{p_s, E_i + S_i - E^{\max}\} & E_i \geq p_s \\ E_i & p_u \leq E_i \leq p_s \\ \min\{p_u, E_i + S_i\} & E_i \leq p_u \end{cases}$$

to satisfy

$$\eta \int_{p_s}^{\infty} (e - p_s) p_E(e) de - \int_0^{p_u} (p_u - e) p_E(e) de = 0$$

Simulations

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$N = 10^4$ *time slots*

$\tau = 10\ ms$

$E_{\max} = 1\ mJ$

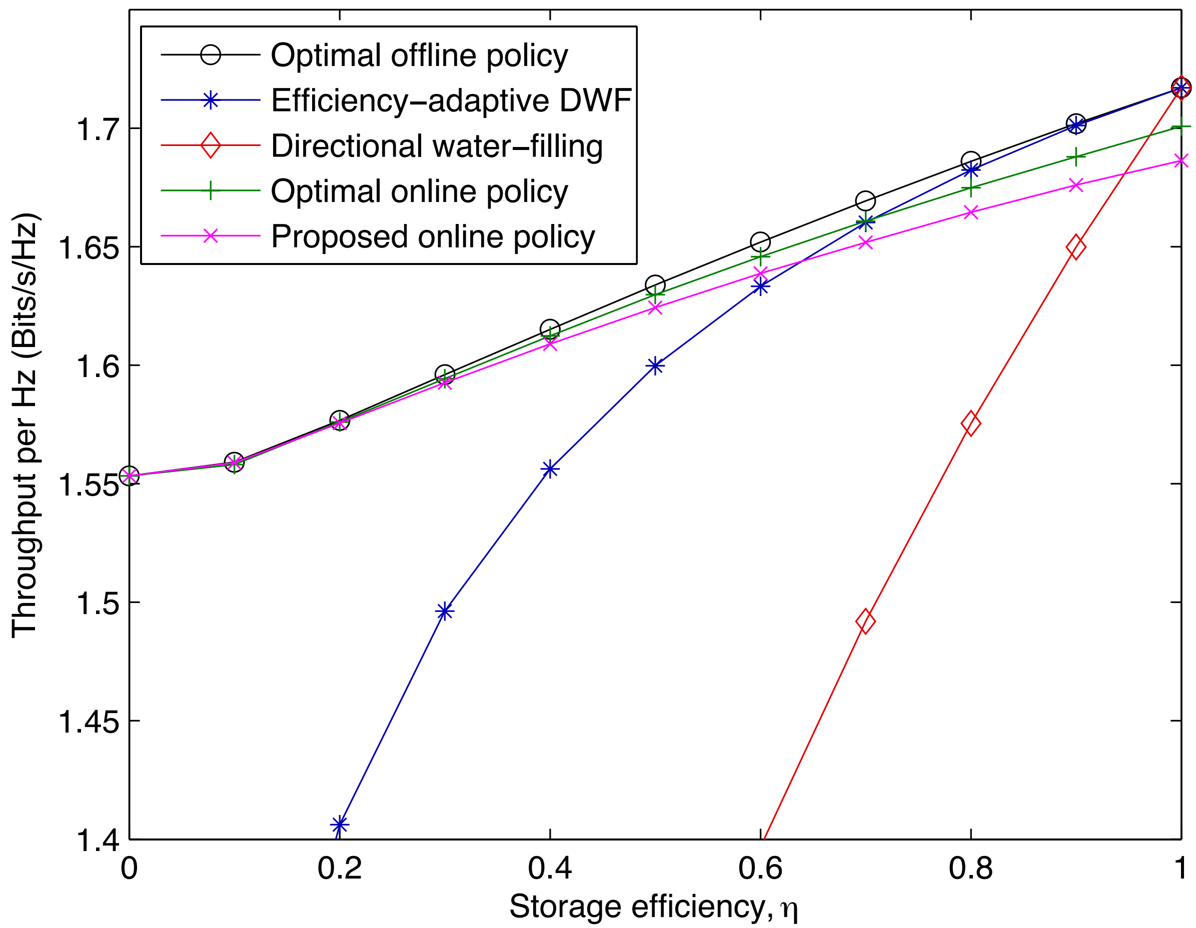
$E_0 = 0$

$E_i \sim i.i.d.\ U[0{,}200]\mu J$

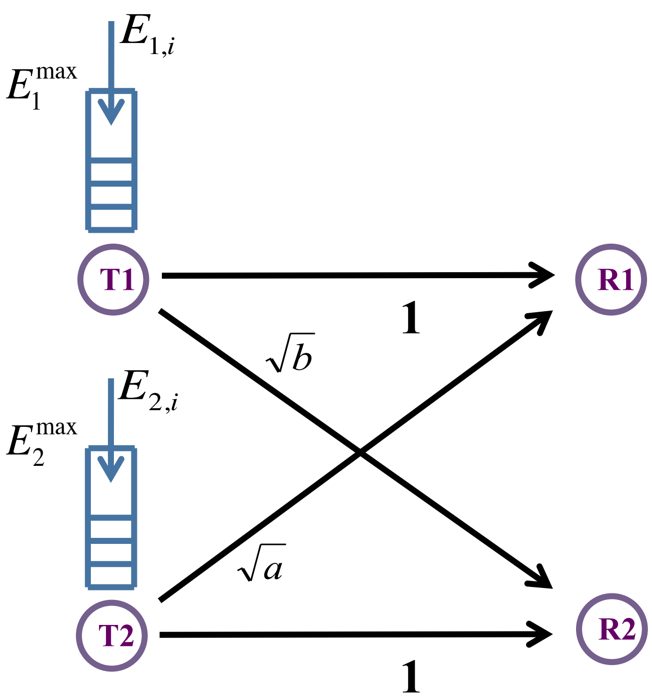
$h = -100\ dB$

$B = 1\ MHz$

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

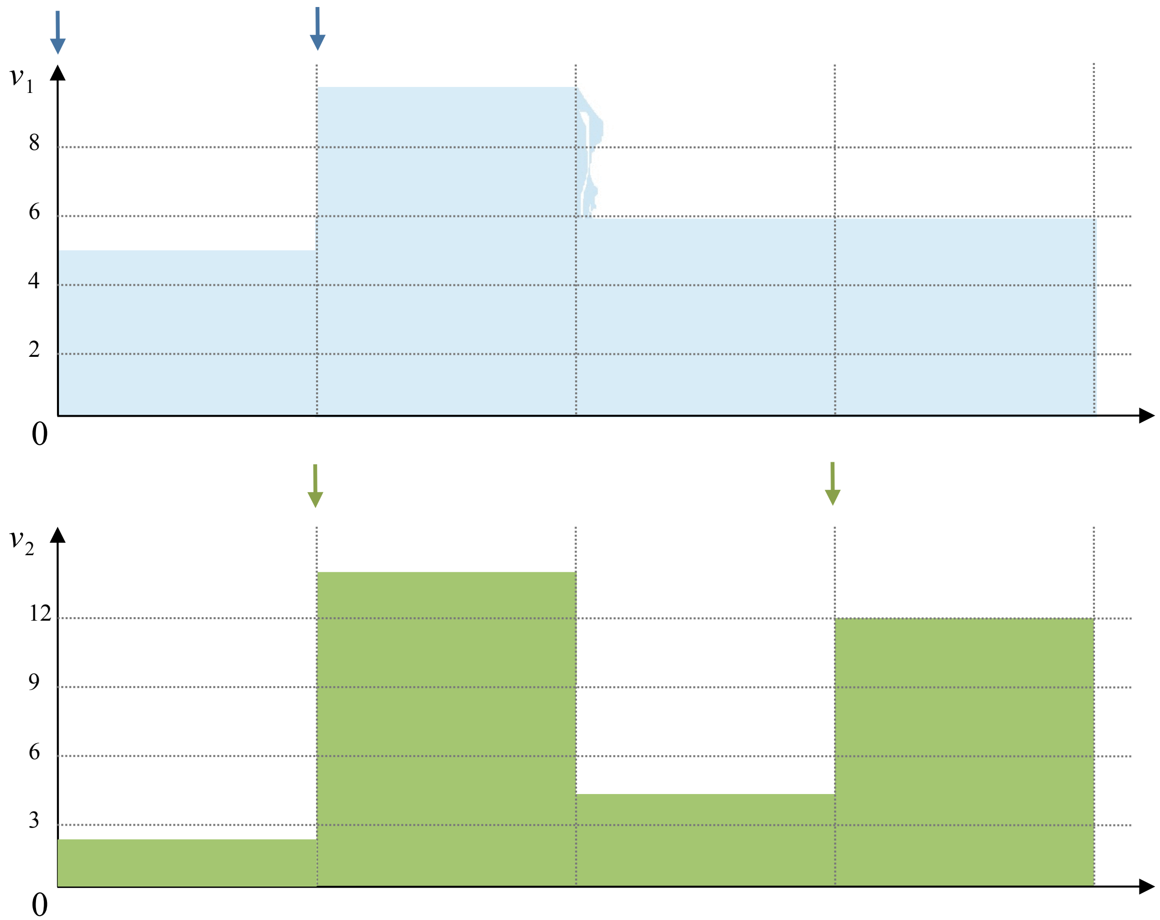


Multiple EH Transmitters



- How to transmit when there are **more than one energy harvesting transmitters** sharing the same medium?
- Many multi-node models, e.g.,
  - MAC and BC [Ozel-Yang-Ulukus '11,'12],
  - Relay [Cui-Zhang '12], [Oner-Erkip '13]
  - Two-way Relay Ch. [Tutuncuoglu-Varan-Yener '15],
  - Interference Channel [Tutuncuoglu-Yener '12]

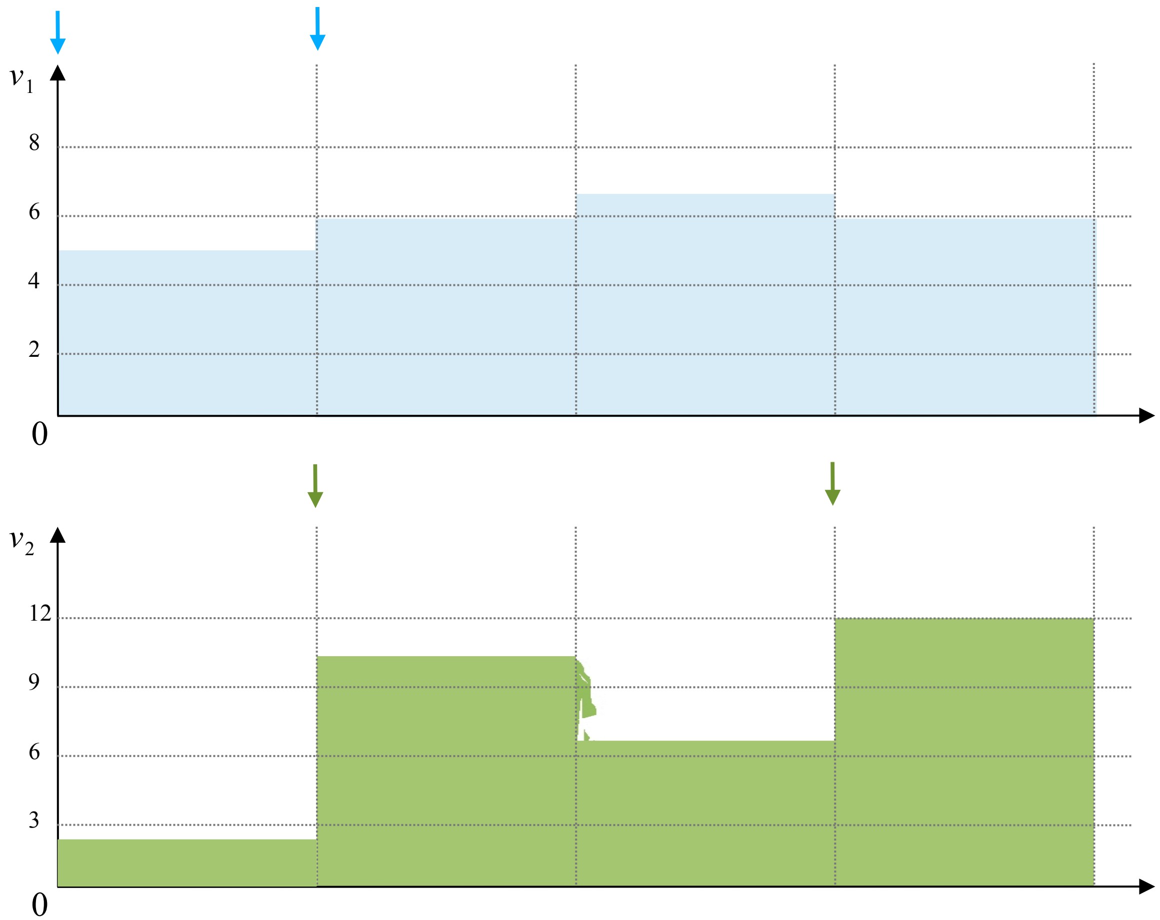
Iterative Generalized Directional Water-filling (IGDWF)



GDWF for

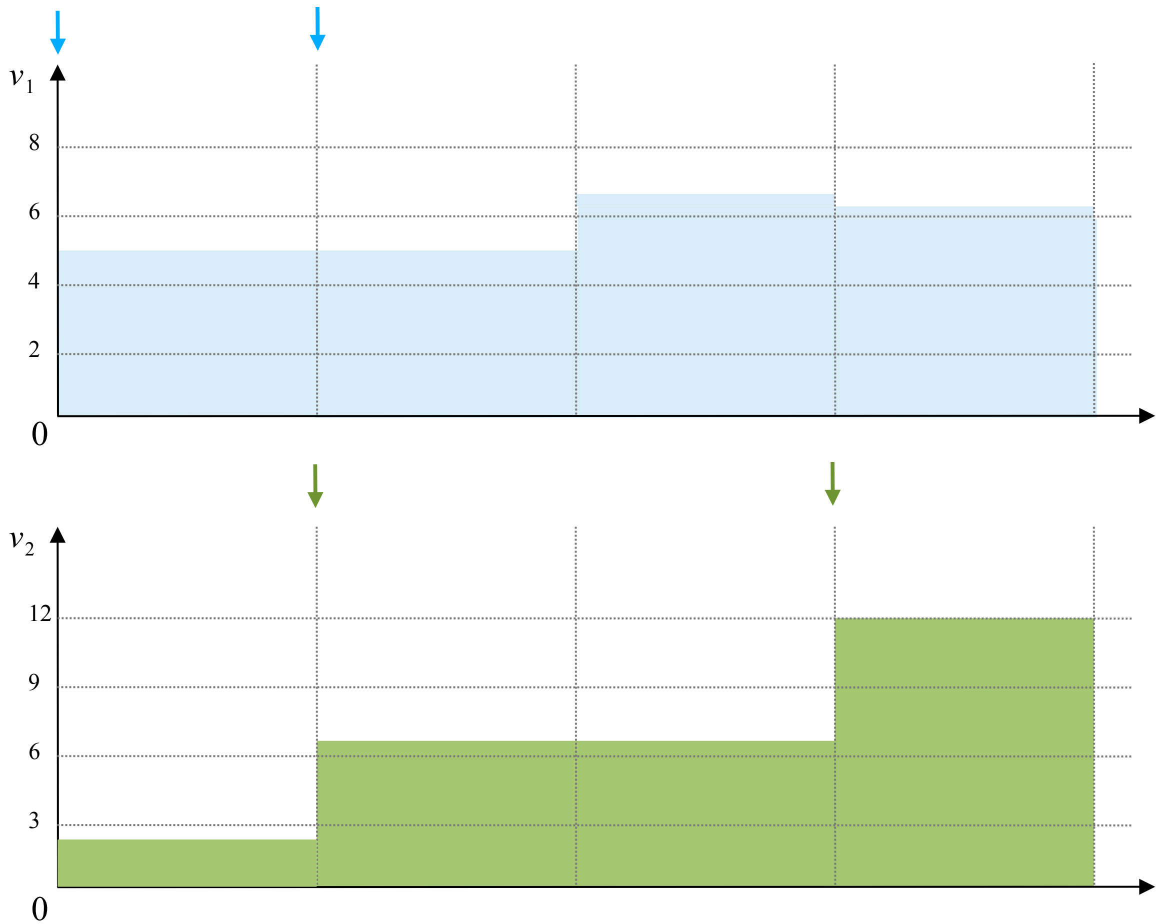
User 1

Iterative Generalized Directional Water-filling (IGDWF)



GDWF for User 2

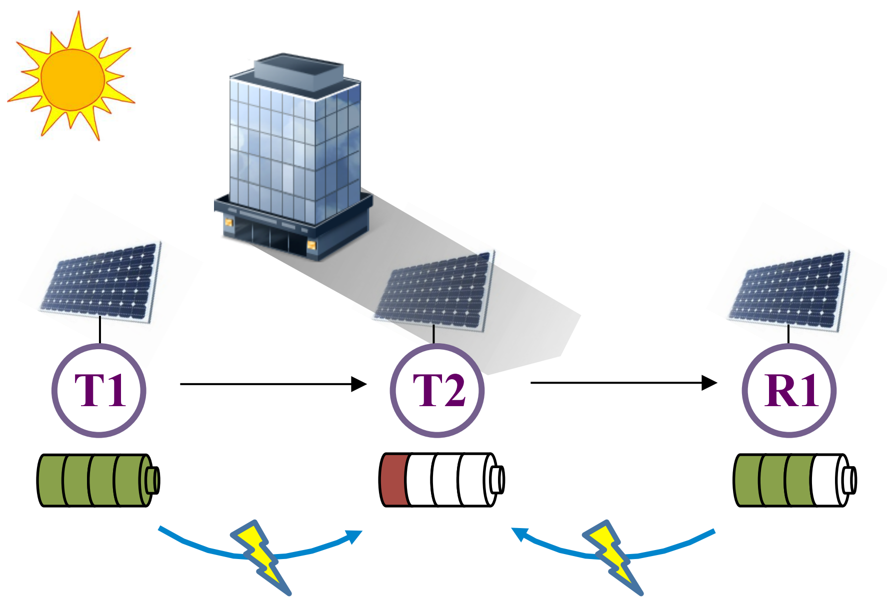
Iterative Generalized Directional Water-filling (IGDWF)



GDWF for User 1

Multiple EH Transmitters: Energy Cooperation

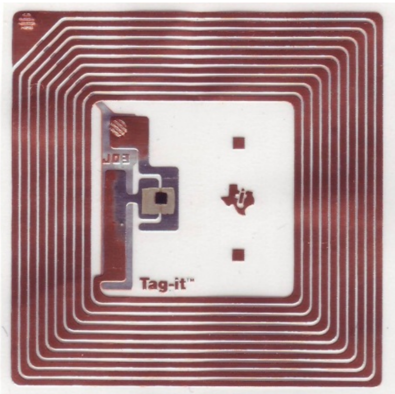
- Intermittent energy ⇒ nodes may be energy deprived!



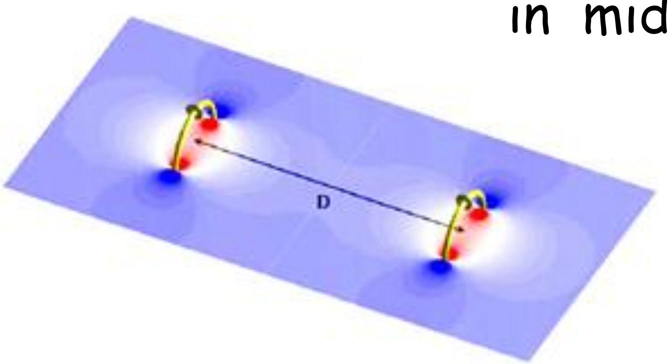
- Energy cooperation between nodes can be very useful!

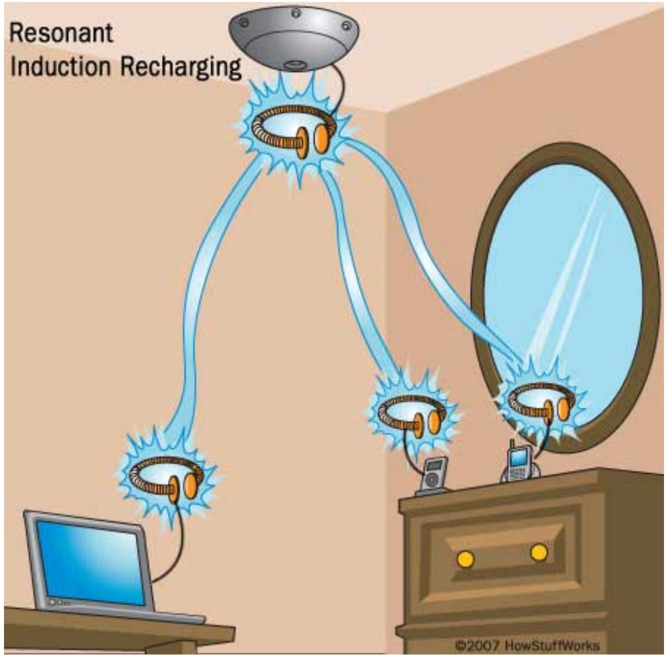
- [Gurakan-Ozel-Ulukus '12]
- [Tutuncuoglu-Y. '13]

Wireless Energy Transfer



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





- 50 percent efficiency at 6 feet (MIT)
- 90 percent efficiency at 3 feet (MIT).
- 75 percent efficiency at 2-3 feet (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

Energy Harvesting and Energy Cooperation (EH-EC)

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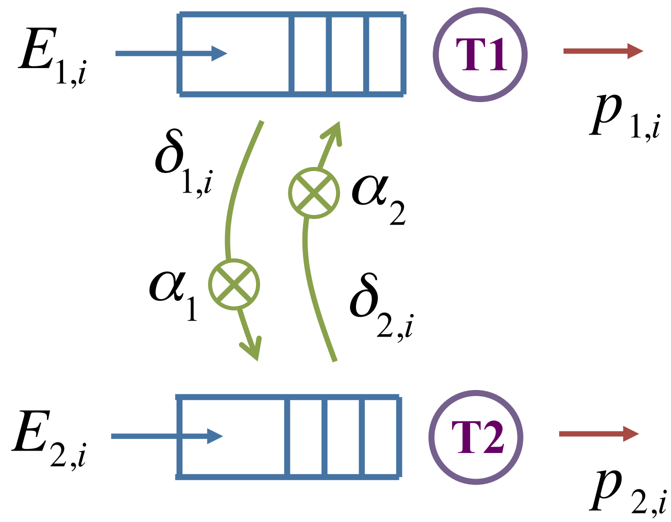
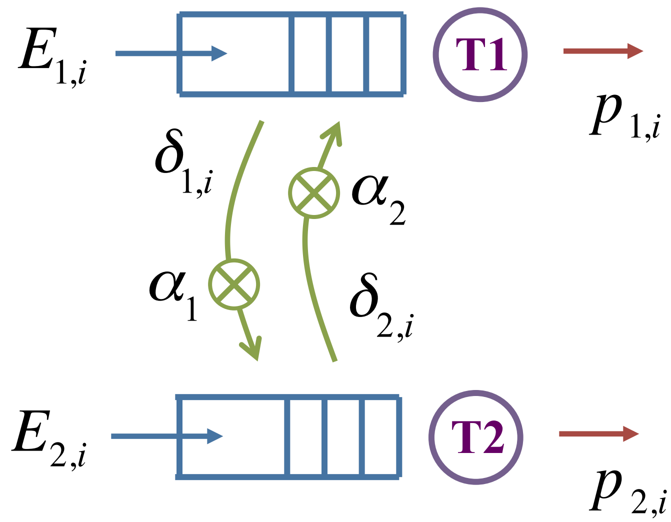
- K transmitters receive energy $E_{j,i}$ at the i^{th} time slot
- In slot i, node k transmits with power $p_{k,i}$



- Transmitters wirelessly transfer energy to each other

EH-EC

- In time slot i, Tk sends $\delta_{k,i}$ to Tj, $k,j = 1,2$, with end-to-end efficiency α_k
- Uni-directional EC is a special case with $\alpha_2 = 0$
- Battery state at time slot i:



$$E_{k,i}^{bat} = \min\left\{E_k^{\max}, E_{k,i-1}^{bat} + E_{k,i} - \delta_{k,i} + \alpha_j \delta_{j,i} - p_{k,i}\right\}$$

Harvested energy

Received and sent energy

Energy used for transmission

EH-EC

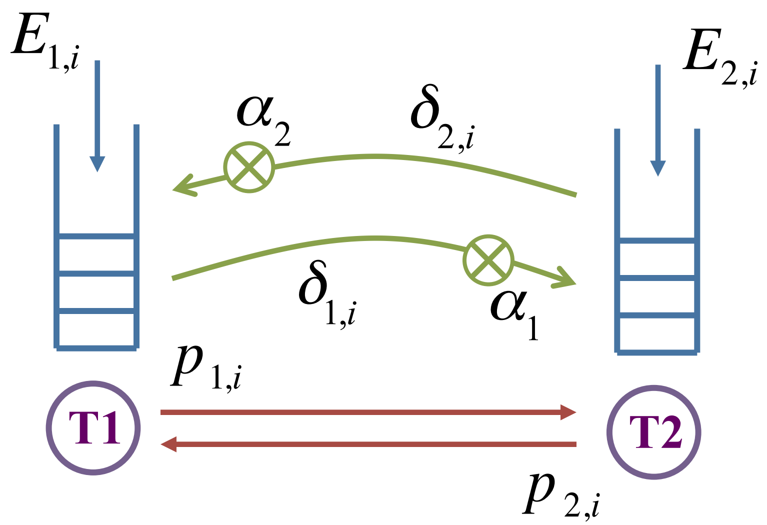
Energy Constraints:

- **Non-negativity:** $p_{k,n} \geq 0,\ \delta_{k,n} \geq 0, \quad k = 1,2, \quad n = 1,\ldots,N$

- **Energy causality:** $E_{k,i}^{bat} = \sum_{n=1}^{i} \left(E_{k,n} + \alpha_j \delta_{j,n} - \delta_{k,n} - p_{k,n} \right) \geq 0$

- **No-Battery-Overflow:** $E_{k,i}^{bat} \leq E_k^{\max}$

EH-EC Two Way Channel



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

- **Sum-rate:** $r^{TWC}(p_1, p_2) = \frac{1}{2}\log\left(1 + \frac{h_1 p_1}{\sigma_2^2}\right) + \frac{1}{2}\log\left(1 + \frac{h_2 p_2}{\sigma_1^2}\right)$

Problem Statement

- Maximize sum-throughput by jointly optimizing the transferred energy and transmit power.

$$\max_{p_{k,i},\ \delta_{k,i}} \sum_{n=1}^{N} r^{TWC}(p_{1,n}, p_{2,n})$$

$$s.t.\ \ p_{k,i} \geq 0, \quad \delta_{k,i} \geq 0,$$

$$\sum_{n=1}^{i}\left(E_{k,n} + \alpha_j \delta_{j,n} - \delta_{k,n} - p_{k,n}\right) \geq 0$$

$$j,k = 1,2, \ \ \mathrm{j} \neq \mathrm{k}, \quad \mathrm{i} = 1,\ldots,N$$

- First assume infinite battery.

Procrastinating Policies

- **Definition:** A procrastinating policy satisfies

$$p_{k,i} - \alpha_j \delta_{j,i} \geq 0, \quad k, j = 1,2, \quad k \neq j$$

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

- In a procrastinating policy, a node *does not transfer energy unless the receiving node intends to use it immediately.*
- **Theorem: (Tutuncuoglu-Y.15): There exists an optimal policy that is procrastinating.**

Decomposition of the Sum-Throughput Problem

- Define consumed powers $\bar{p}_{k,i} = p_{k,i} + \delta_{k,i} - \alpha_j \delta_{j,i}$
- Sum-throughput maximization can be decomposed as

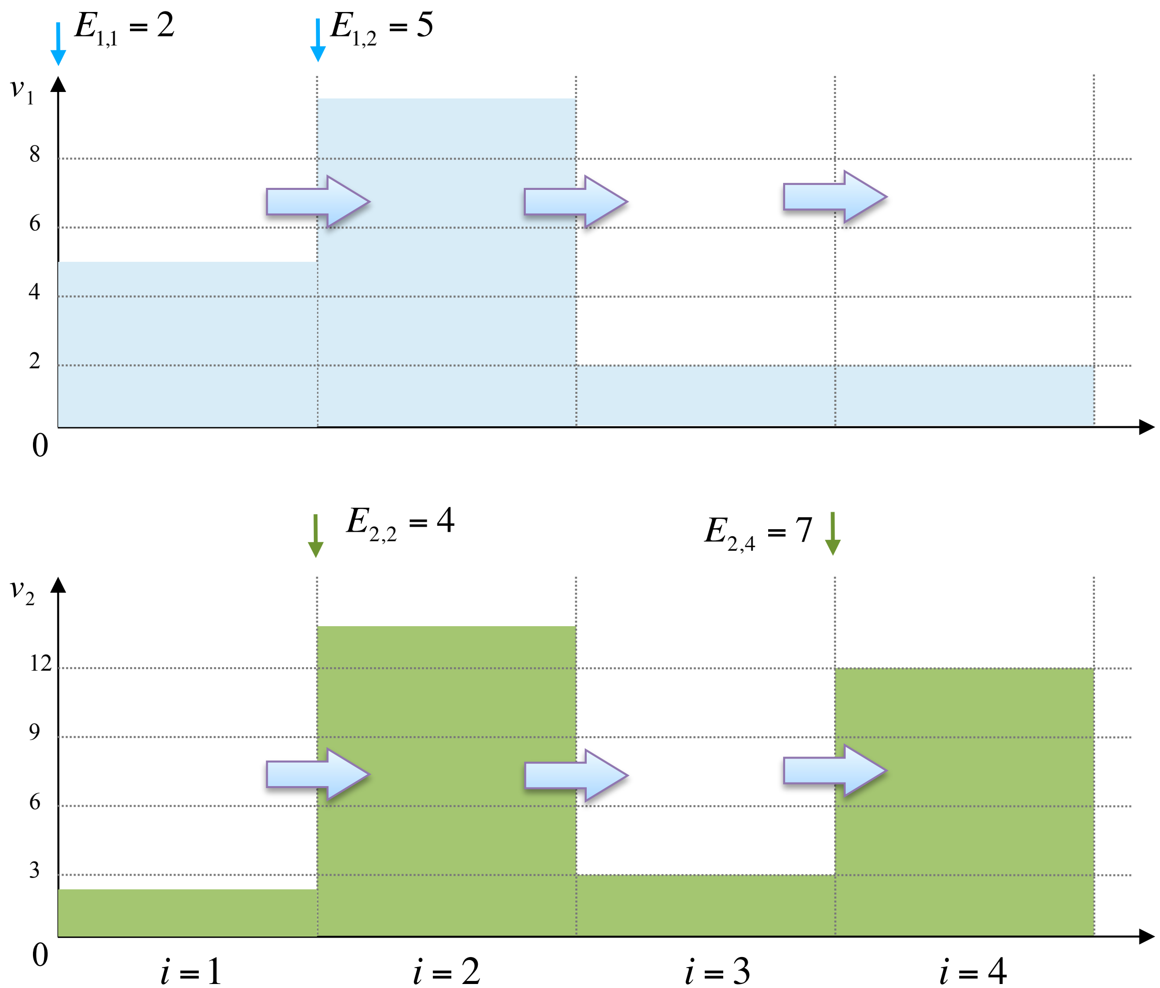
$$\max_{\{\bar{p}_{k,i}\}} \sum_{i=1}^{N} r_S(\bar{p}_{1,i}, \bar{p}_{2,i})$$
$$s.t. \sum_{n=1}^{i}\left(E_{k,n} - \bar{p}_{k,n}\right) \geq 0, \quad k = 1,2, \quad i = 1,\ldots,N,$$
$$\bar{p}_{k,i} \geq 0, \quad k = 1,2, \quad i = 1,\ldots,N.$$

$$r_S = \max_{\delta_{k,i}} \mathrm{r}^{TWC}\left(\left[\bar{p}_{k,i} + \alpha_j \delta_{j,i} - \delta_{k,i}\right]\right)$$
$$s.t. \quad \delta_{k,i} \geq 0, \quad \bar{p}_{k,i} - \delta_{k,i} \geq 0,$$
$$k = 1,2.$$

Power Allocation
Solved via IGDWF

Energy Transfer
Solved directly (single slot)

EC-EH-TWC



$\alpha_1 = 0.5$

$\alpha_2 = 0.5$

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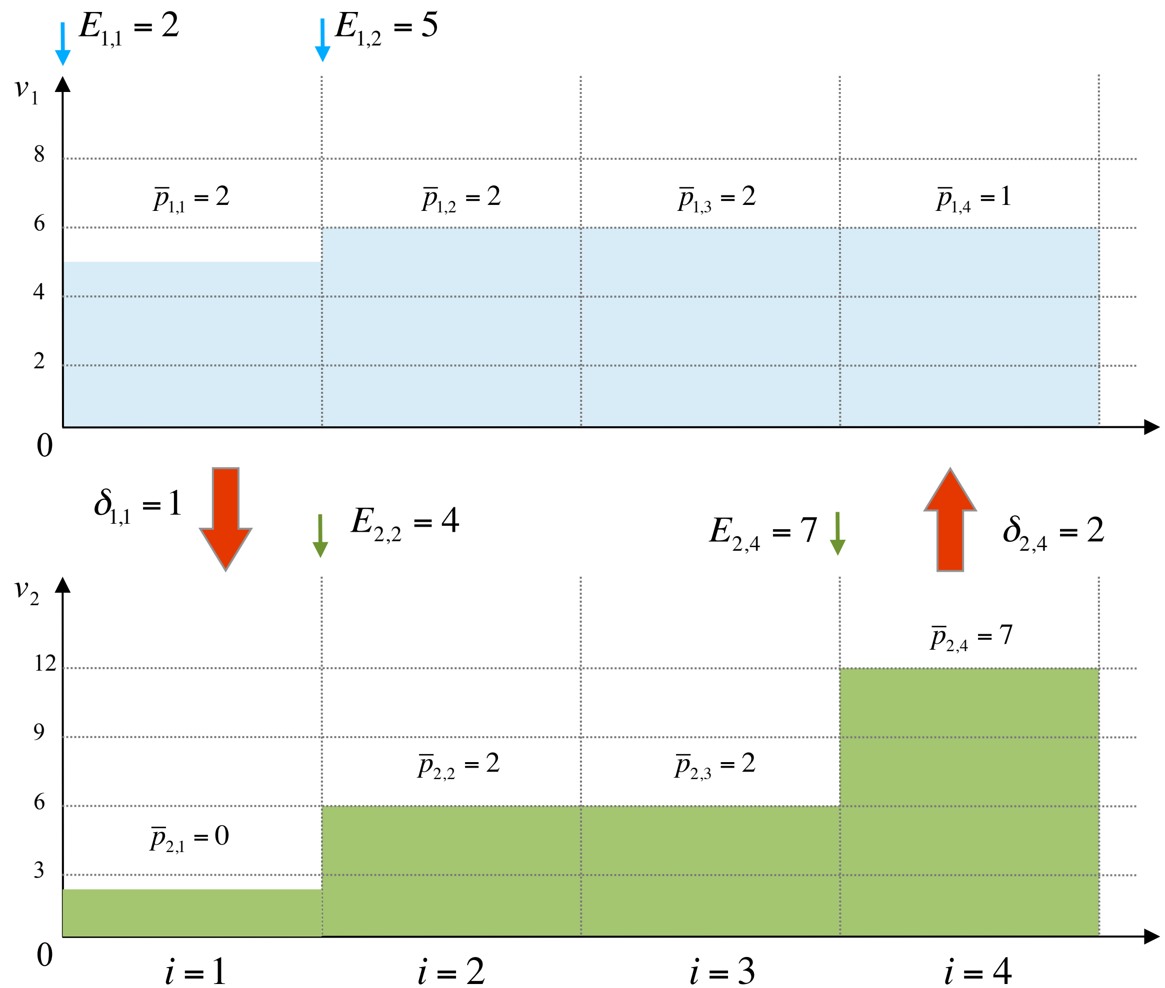
EC-EH-TWC



$\alpha_1 = 0.5$

$\alpha_2 = 0.5$

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Finite Battery Extension [Tutuncuoglu-Y.15]

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- Problem definition:

$$\max_{p_{k,i},\, \delta_{k,i}} \sum_{n=1}^{N} r^{TWC}(p_{1,n}, p_{2,n})$$

$$s.t. \;\; p_{k,i} \ge 0, \quad \delta_{k,i} \ge 0,$$

$$0 \le \sum_{n=1}^{i} \left(E_{k,n} + \alpha_j \delta_{j,n} - \delta_{k,n} - p_{k,n}\right) \le E_{k,\max}$$

$$j,k = 1,2, \;\; j \ne k, \quad i = 1,\ldots,N$$

- Postponing energy transfers may result in **battery overflow**
- **Pure procrastinating policies no longer optimal**

Partially Procrastinating Policies

- Split transferred energy as $\delta_{k,i} = \gamma_{k,i} + \rho_{k,i}, \quad \gamma_{k,i}, \rho_{k,i} \geq 0.$

  $\gamma_{k,i}$: Immediately consumed comp. $\rho_{k,i}$: Stored comp.

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

$$p_{k,i} - \alpha_j \gamma_{j,i} \geq 0, \quad \gamma_{k,i}\gamma_{j,i} = 0, \quad k, j = 1,2, \quad k \neq j$$
$$\rho_{k,i}\left(E_k^{\max} - S_{k,i}\right) = 0, \quad k = 1,2,$$

- Consumed comp. **must immediately be used**,
- Stored comp. **must be zero unless battery is full.**
- Problem solved via **2D directional water-filling with restricted transfers**

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Numerical Results

- **TWC:**

$N = 100, \quad T = 1\,\text{sec},$

$h_1 = -100\,dB,$

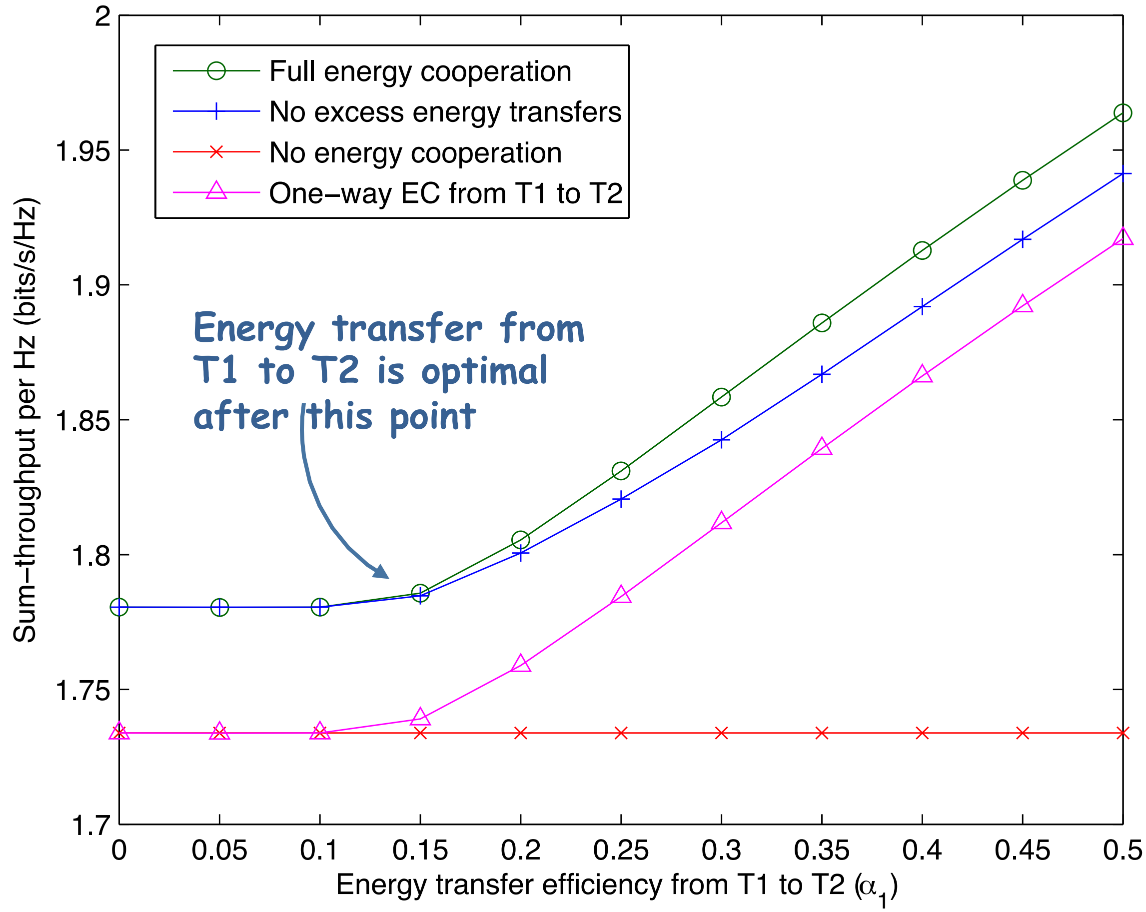
$h_2 = -100\,dB,$

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

$E_{1,i} \sim U[0,10]mJ,$

$E_{2,i} \sim U[0,10]mJ,$

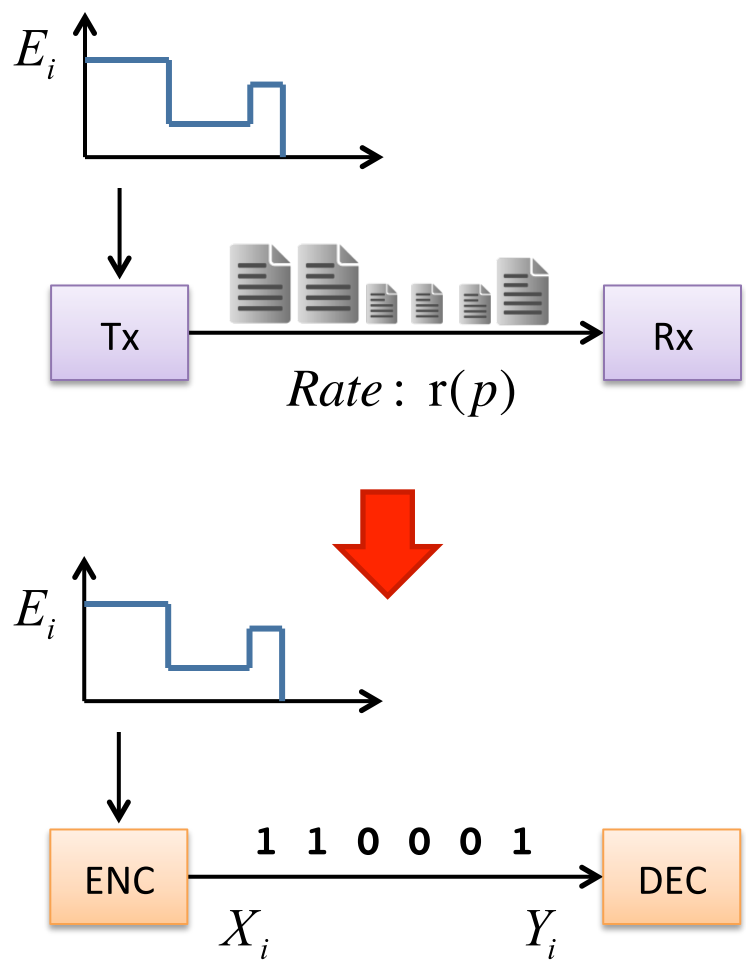
$\alpha_2 = 0.5$



Information Theory of EH Transmitters

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

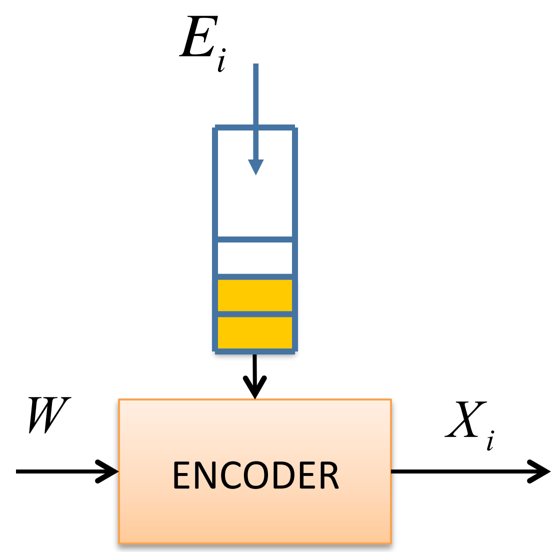
- What if **energy harvesting is at the symbol level**, i.e., each input symbol is individually limited by EH constraints?



Energy Harvesting (EH) Channel

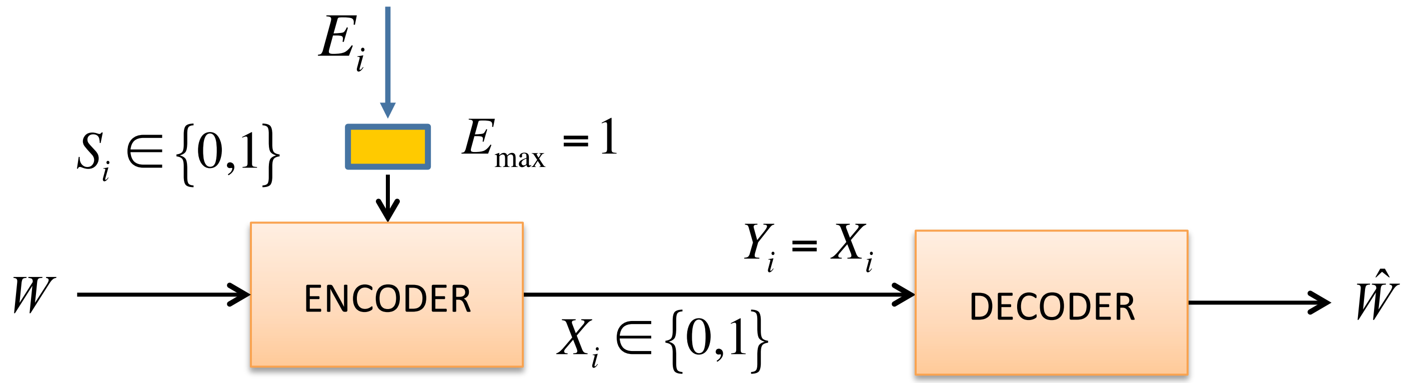
[Tutuncuoglu-Ozel-Ulukus-Y. '13]

- 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)

Binary Noiseless EH Channel



[Tutuncuoglu-Ozel-Y.-Ulukus '13, '14, 17']

- Transmitting $X_i \in \{0,1\}$ requires X_i units of energy
- Unit battery, $E_{max} = 1$
- Binary noiseless channel, $Y_i = X_i$

Conclusion

- New wireless communications paradigm: energy harvesting nodes
- New design insights arising from
  - new energy constraints
  - energy storage limitations and inefficiencies
  - interaction of multiple EH transmitters
  - energy cooperation
- New problems in the information theory domain
- Still lots of open problems related to all layers of the network design.

Acknowledgements

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- Collaborators on papers summarized in this talk are: Omur Ozel, Kaya Tutuncuoglu, Sennur Ulukus, Jing Yang.

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