Powering the Internet of Things: Efficient and Reliable Wireless Communications with Unreliable Power Supply

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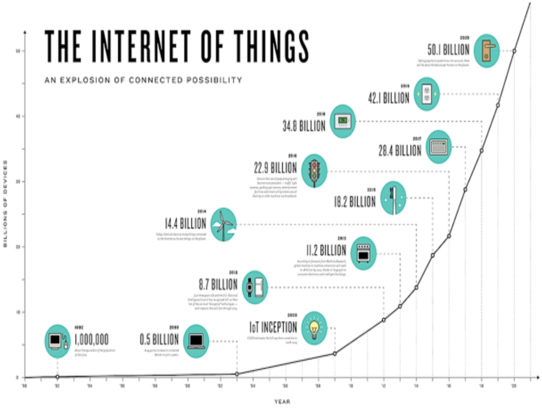
Outline

Internet of Things



- By 2020, **over 50 billion intelligent devices** (Cisco) will connect to and exchange information over the Internet versus a projected 7.3 billion tablets, smartphones and PCs (Gartner), with an **economic impact of nearly USD 2 trillion** (Gartner).
- This huge cohort of "things" could result in **the disposal of about 300 million batteries a day** across the globe.

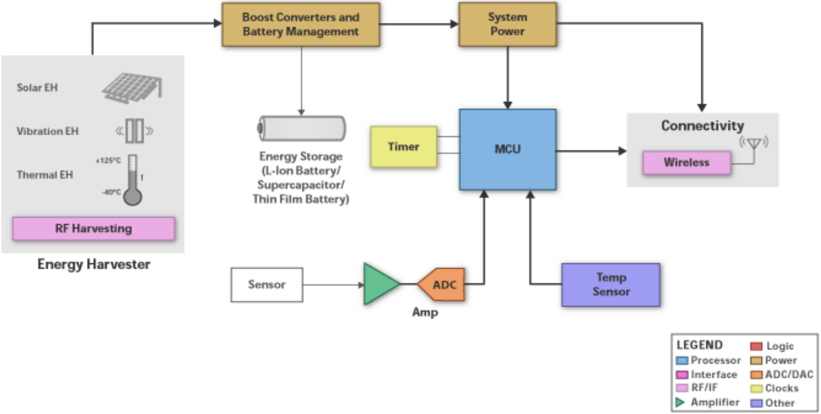
"Free?" Energy

Energy-Harvesting Sources Today			
Energy Source	**Characteristics**	**Efficiency**	**Harvested Power**
Light	Outdoor Indoor	10~24%	100 mW/cm^2 100 μW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 μW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 μW/cm^2 0.001 μW/cm^2

Courtesy of Texas Instruments

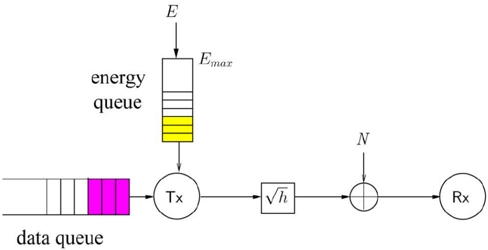
- Harvesting energy from renewable energy resources is an appealing solution to energize IoT devices.
- Energy sources include Solar, thermal, mechanical, and **RF transmissions**.

Energy Harvesting Block Diagram



A typical energy harvesting system consists of a transducer device and a small rechargable battery to store collected energy.

"Not so Free" Energy



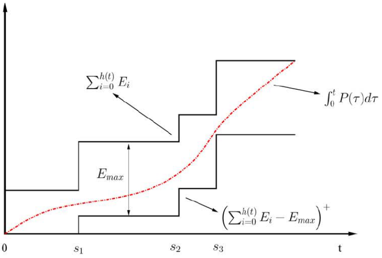


Figure: Working with random energy/data arrivals [2].

For survey on the past work see:

1. M. -L. Ku, W. Li, Y. Chen and K. J. R. Liu, *Advances in Energy Harvesting Communications: Past, Present, and Future Challenges*, IEEE Communications Surveys & Tutorials, Second quarter 2016.
2. S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, K. Huang, *Energy Harvesting Wireless Communications: A Review of Recent Advances*, IEEE Journal on Selected Areas in Communications, March 2015.

Channel Sensing and Communication over a Time-Correlated Channel with an Energy Harvesting Transmitter

Challenge

Observation

Channel state information (CSI) acquisition improves performance significantly.

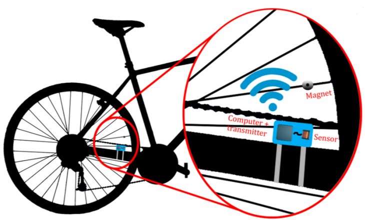
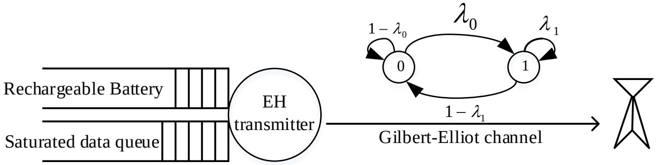


Figure: Wireless cycle computer.

System Model



- Time-varying finite state (Gilbert-Elliot) channel.
- Channel state, G_t: Markov chain with two states: GOOD state (1) and BAD state (0).
- If $G_t = 1$: R bits per time slot; If $G_t = 0$: zero bits.
- E_t: binary harvested energy at time t; with $\Pr(E_t = 1) = q$.
- Transmission: unit energy; sensing: $0 < \tau < 1$ units.
- Finite size battery.
- ACK/NACK feedback after each transmission.

POMDP

- Partially Observable Markov Decision Process (POMDP).
  - Introduce belief state on channel state.
    - Continuous state MDP.
- System state: $S_t = (B_t, X_t)$
  - B_t: battery level at time t.
  - X_t: *belief* about channel state at time t.
    - Conditional probability of channel being in a GOOD state, given the history. $P[G_t = 1 | H_t] = p$, where H_t is history.

Transmission Policy: Deferring

At time slot t, Tx takes action $A_t \in \{D, O, T\}$:

- 1) **Defer transmission (D)**
  - No transmission
  - No feedback.
  - Belief is updated as $J(p) = p\lambda_1 + (1-p)\lambda_0$.

Transmission Policy: Sensing

- 2) **Sense the channel and transmit opportunistically (O)**

  - if channel is GOOD:
    - Transmit $(1-\tau)R$ bits in the remainder of the slot.
    - Consume one energy unit in total.
    - $p = \lambda_1$

  - if channel is BAD:
    - Remains silent.
    - Saves $1-\tau$ units of energy.
    - $p = \lambda_0$

Transmission Policy: Transmit without sensing

- 3) **Transmit without sensing (T)**
  - Transmit R bits without sensing.
  - Learns channel state thanks to the feedback.
  - Receive ACK: $p = \lambda_1$; receive NACK: $p = \lambda_0$.

MDP Formulation

- State of the system: $S_t = (B_t, X_t)$

Discounted Reward (β: discount factor)

$$V^{\pi}(b,\ p) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t R(S_t, A_t) | S_0 = (b,\ p)\right],$$

for all $b \in \{0, \tau, \ldots, B_{max}\}$ and $p \in [0,\ 1]$, where

$$R(S_t, A_t) = \begin{cases} X_t R & \text{if } A_t = T \text{ and } B_t \geq 1, \\ (1-\tau) X_t R & \text{if } A_t = O \text{ and } B_t \geq 1, \\ 0 & A_t = D. \end{cases}$$

Action-Value Function

- $V_A(b,\ p)$: Action-value function
  - expected infinite-horizon discounted reward of taking action A at state $(b,\ p)$.

Bellman optimality equation

$$V(b,\ p) = \max_{A \in \{D,O,T\}} \{V_A(b,\ p)\}.$$

Structure of the Optimal Policy

Theorem

For any $p \in [0,\ 1]$ *and* $b \geq 0$*, there exist thresholds* $0 \leq \rho_1(b) \leq \rho_2(b) \leq \rho_3(b) \leq 1$*, such that, for* $b \geq 1$

$$\pi^*(b,\ p) = \begin{cases} D, & \textit{if } 0 \leq p \leq \rho_1(b) \textit{ or } \rho_2(b) \leq p \leq \rho_3(b) \\ O, & \textit{if } \rho_1(b) \leq p \leq \rho_2(b), \\ T, & \textit{if } \rho_3(b) \leq p \leq 1, \end{cases} \tag{1}$$

and for $\tau \leq b < 1$*,*

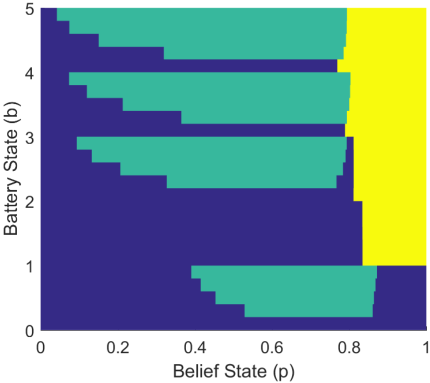
$$\pi^*(b, p) = \begin{cases} D, & \textit{if } 0 \leq p \leq \rho_1(b) \textit{ or } \rho_2(b) \leq p \leq 1, \\ O, & \textit{if } \rho_1(b) \leq p \leq \rho_2(b). \end{cases} \tag{2}$$

- For $b \geq 1$, at most three thresholds.
- For $b < 1$, at most two thresholds.

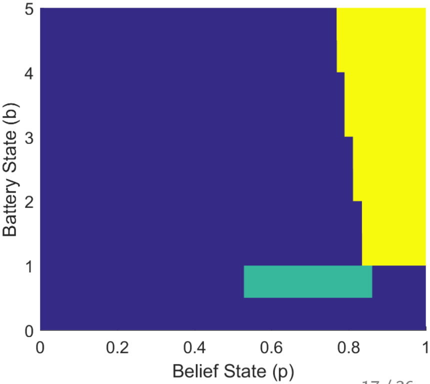
Numerical Results: Effect of Sensing Duration

Optimal thresholds for taking actions D (blue), O (green), T (yellow) for $B_{max} = 5$, $\beta = 0.98$, $\lambda_1 = 0.9$, $\lambda_0 = 0.6$, $R = 3$ and $q = 0.1$.

- $\tau = 0.2$.

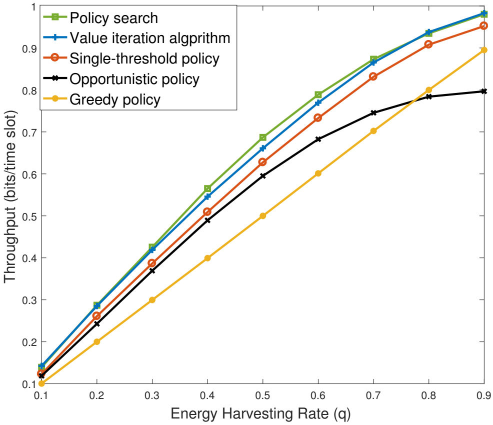


- $\tau = 0.5$.



Numerical Results: Throughput

$B_{max} = 5,\ \tau = 0.2,\ \beta = 0.999,\ \lambda_1 = 0.8,\ \lambda_0 = 0.2,\ R = 2.$



- Policy search: Optimal thresholds.
- Value iteration algorithm: Bellman optimality equations.
- Single-threshold policy: only defer or transmit.
- Opportunistic policy: always sense the channel.
- Greedy policy: transmit whenever there is energy.

Main Results

M. Abad, O. Ercetin, D. Gunduz, **Channel Sensing and Communication over a Time-Correlated Channel with an Energy Harvesting Transmitter**, *IEEE Transactions on Green Communications and Networking*,, 2017.

- Time-varying channel with memory (Gilbert-Elliot channel).
- Formulate optimal communication problem as a POMDP.
- Optimal policy is a threshold type policy on the belief state on the channel state.
- Low complexity numerical solution using policy search (reinforcement learning technique).

Reliable Wireless Information and Power Transfer using Hybrid ARQ

Wireless Energy Transfer

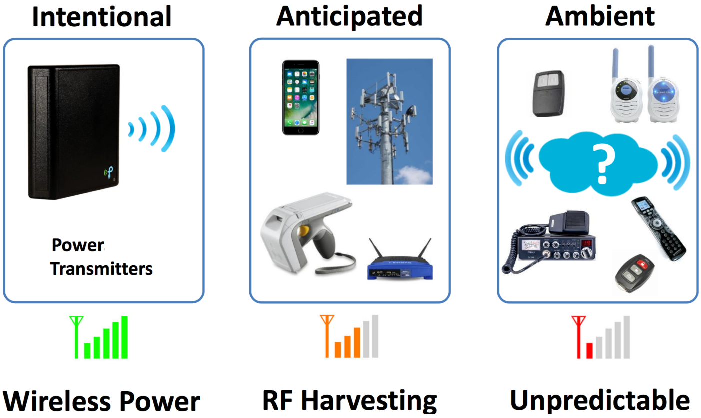
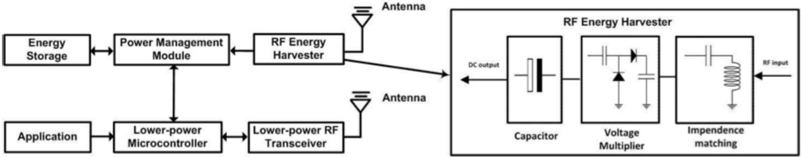


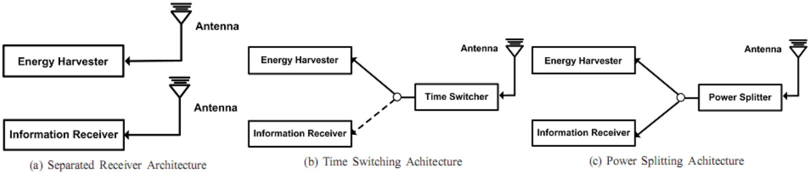
Figure: Different forms of WET. Courtesy of Powercast

RF Energy Harvesting



- Applications in RFID, low-power sensors.
- The antenna can be designed to work on either single frequency or multiple frequency bands.
- The impedance matching is a resonator circuit operating at the designed frequency to maximize the power transfer between the antenna and the multiplier.
- Voltage multiplier converts RF (AC) to DC, and capacitor smooths the voltage.
- Efficiency depends on the efficiency of antenna, accuracy of impedance matching and power efficiency of the voltage multiplier. **0.4% at - 40dBm, above 18.2% at - 20dbm, over 50% at -5dBm.**

RF Energy Harvesting Architectures



Several receiver architectures were proposed for the RF energy harvesting node

- *Separated receiver architecture*, where the information receiver and the harvesting circuit is separated and each is equipped with its own antenna.
- *Co-located receiver architecture*, where the information receiver and the harvesting circuit use the same antenna for information decoding and energy harvesting.

System Model

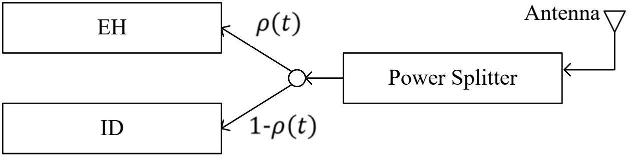


Figure: EH receiver

- Transmitter:unlimited power supply, Receiver: EH (SWIPT)
- Time-varying two-state channel; unknown at receiver and transmitter.
- GOOD state (1) and BAD state (0).
- If $G_t = 1$: R_1 bits per time slot; If $G_t = 0$: $R_2 < R_1$ bits.
- Power split ratio: $0 \leq \rho(t) \leq 1$.
- $\rho(t) = 1$: EH; $\rho(t) = 0$: ID; $0 < \rho(t) < 1$: split

HARQ-IR

Reliability

For reliability, hybrid ARQ is employed. Since CSI is unknown, HARQ with incremental redundancy (IR) is used for its robustness against unknown CSI.

- Let $R(t) = \log(1 + P|g(t)|^2)$ be the instantaneous rate.
- each message W is encoded into $\mathbf{x} = [x^1, \ldots, x^M]$.
- $\mathbf{x}$ is divided into M blocks, with length N, and variable redundancy.
- After r retransmissions, $\sum_{k=1}^{r} R(t_k)$ of mutual information is accumulated.
- If $\sum_{k=1}^{r} R(t_k) > R_1$ message is decoded successfully, ACK is sent. Otherwise, NACK is sent for further retransmissions.

Energy Consumption and Rate model

- If channel is GOOD, $\rho(t)e$ is harvested, $e \geq 1$.
- BAD channel: no energy.
- ID circuit consumes 1 unit of energy per each ID action.
- Decoding cost is $E_d \geq 1$.
- $R^H(\rho)(R^L(\rho))$: ρ dependent rate at GOOD (BAD) state.

$$R^H(\rho) = \log(\rho + (1-\rho)2^{R_1}), R^L(\rho) = \log(\rho + (1-\rho)2^{R_2}). \tag{3}$$

- Battery $B(t)$ and mutual information $I(t)$ evolve as:

$$B(t) = \begin{cases} B(t-1) + \rho(t)e - \mathbb{1}_{\rho(t)\neq 1}, & \text{if } G_t = 1 \\ B(t-1) - \mathbb{1}_{\rho(t)\neq 1}, & \text{if } G_t = 0 \end{cases}, \tag{4}$$

$$I(t) = \begin{cases} \min(I(t-1) + R^H(\rho(t)), R_1), & \text{if } G_t = 1 \\ \min(I(t-1) + R^L(\rho(t)), R_1), & \text{if } G_t = 0 \end{cases}. \tag{5}$$

Markov Decision Process (MDP)

Objective

Optimize $\rho(t)$, for all t, so that the transmission is successfully decoded with a minimum delay at the receiver.

- Let $\mathbb{P}\left[G_t = 1\right] = \lambda$.
- b: total residual battery level; m: total accumulated mutual information. Let $(b,\ m)$ be the state of the Markov chain.
- $V^{\pi}(b,\ m)$: expected discounted reward with initial state $S_0 = (0,0)$ under policy π with discount factor $\beta \in [0,1)$.
- Define: $V(b,\ m) = \max_{\pi} V^{\pi}(b,\ m),\ \forall b \in [0,\infty),\ \forall m \in [0,\ R_1]$
- Bellman equation: $V(b,m) = \max_{0\leq\rho\leq 1} V_{\rho}(b,m)$
- $V_{\rho}(b,m) = U((b,\ m),\rho) + \beta\mathbb{E}\left[V(\acute{b},\ \acute{m})|S_0 = (0,\ 0)\right]$

$$U((b,\ m),\rho(t)) = \begin{cases} 0, & \text{if } b \geq E_d, \text{ and } m \geq R_1, \\ -1, & \text{if otherwise.} \end{cases} \quad (6)$$

MDP fails!

Numerical Solution

Standard tool for obtaining the solution of the MDP is to use numerical methods such as value iteration algorithm to solve the Bellman equation.

However, due to

- Curse of dimensionality:
  - $b \in [0, \infty)$; $m \in [0,\ R_1]$; and $0 \leq \rho \leq 1$.
  - state and decision space continuous.
- Large β
  - To approximate the average reward, $\beta \to 1$.
  - Covergence time very long.

It is not possible to solve MDP.

Absorbing Markov Chain (MC)

Definition

In an absorbing MC, there are two sets of states: transient and absorbing states. If the MC enters an absorbing state, it can never leave!

- If the receiver has E_d units of energy and R_1 bits of information, then decoding is successful.
- $(b \geq E_d, m \geq R_1)$ absorbing states.
- Find the expected number of transitions until hitting an absorbing state (i.e., successful decoding).
- Let π be a policy that chooses ρ at state (b, m). Mean time to absorption:

$$k_{b,m}^{\pi} = 1 + \lambda k_{b-1_{\rho \neq 1}+\rho e, m+R^H(\rho)} + (1-\lambda) k_{b-1_{\rho \neq 1}, m+R^L(\rho)} \tag{7}$$

Structure of the Optimal Policy

- π^{split}: always splits: $0 < \rho < 1$.
- $\pi^{no-split}$: always chooses $\rho = 0$.
- We show that $k_{b,m}^{\pi^{no-split}} \leq k_{b,m}^{\pi^{split}}$.
- Optimal policy at any (b,m) either chooses $\rho = 1$ or $\rho = 0$.
  - 2- dimensional *uncountable* state MDP with *continuous* decisions reduces to a 2- dimensional *countable* state MDP with *binary* decisions.
- By evaluating and comparing $k_{b,m}^{\rho}$, $\rho = 0, 1$, we find:

Family of optimal policies

Any policy satisfying the following properties is optimal.

1. If $B < 1$ or $I = R_1$, it chooses $\rho = 1$.
2. If $B > m$, it chooses $\rho = 0$.
3. If $(1 \leq B \leq m,\ 0 \leq I \leq R_1 - 1)$, chooses either $\rho = 0$ or $\rho = 1$.

Discussion

Family of optimal policies

The findings show that the optimal policy is not unique and there exists a family of optimal policies achieving the minimum number of re-transmissions. Examples of such policies are:

- Battery First (BF):harvest energy until E_d units of energy is acquired, then starts accumulating the mutual information.
- Information First (IF): the receiver always accumulates mutual information unless $b = 0$ or $m = R_1$.
- Coin Toss (CT): harvest energy when $b = 0$ or $m = R_1$, while it accumulates mutual information when $b = E_d + 1, E_d + 2, \ldots$. Otherwise, tosses a fair coin to choose between EH or ID.

Correlated Channel

- $\mathbb{P}[G_t = 1 | G_{t-1} = 1] = \lambda_1$ and $\mathbb{P}[G_t = 1 | G_{t-1} = 0] = \lambda_0$.

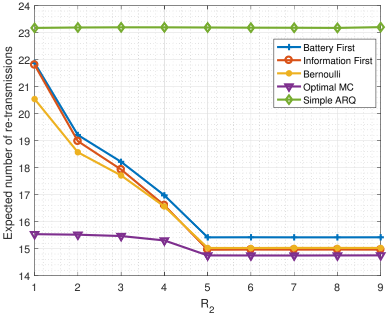
split or not?

Again do not split the incoming power.

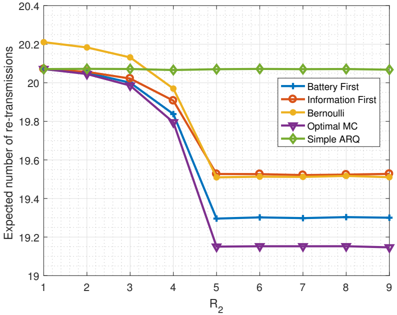
- Due to correlation, previous state of the channel provides information about the current channel state.
- Let (b, m, G) be the state of the absorbing MC.
- In this case, simple to implement policies as in the case of i.i.d. are not optimal. Since those policies are not intelligent to use the correlation information.

Correlated Channel

- Expected number of re-transmissions respect to correlation.



(a) $\lambda_0 = 0.7$ and $\lambda_1 = 0.2$.



(b) $\lambda_0 = 0.2$ and $\lambda_1 = 0.7$.

Main Results

M. Abad, O. Ercetin, T. Elbatt, M. Nafie, *SWIPT using Hybrid ARQ over Time Varying Channels*, submitted to IEEE Transactions on Green Communications and Networking.

- SWIPT enabled receiver utilizing hybrid ARQ.
- Time-varying channel with and without memory.
- Formulate the problem as an MDP.
- Reduce the dimensionality of the problem.
- Optimality of a simple-to-implement algorithm is shown.

Future Directions

- EH communications becoming a mature area with information/communication theoretical aspects well established.
- EH computing is still in its infancy.
  - Power-neutral, intermittent computing for very small IoTs.
  - Mobile Edge Computing with Power Transfer for augmented reality, etc., computation-intensive app.
- More efficient coding for backscatter communications.
- Interaction with upper layer protocols, e.g., TCP/IP or routing over EH IoTs.

Acknowledgements

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