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Energy Harvesting Wireless Networks with Correlated Energy Sources

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Outline

Motivation

- By 2020, **over 50 billion intelligent devices** connected to the Internet.
- **Disposal of about 300 million batteries a day** across the globe.
- Early works on sensor network lifetime maximization.
- Harvesting energy from renewable energy resources is an appealing solution.

Challenges and Previous work

- Energy arrives at random times, and in random and minuscule amounts.
- Significant past research on how to best manage networks with this random energy source.
  - What is the best duty cycle?
    V. Sharma, et al.,"Optimal energy management policies for energy harvesting sensor nodes," IEEE TWC, 9(4), 2010.
  - What is the best channel access strategy?
    O. Ozel, et al., "Transmission with energy harvesting nodes in fading wireless channels: Optimal policies," IEEE JSAC, 29(8), 2011.
  - What is the best routing strategy?
    L. Lin, N. Shroff, R. Srikant, "Asymptotically optimal power-aware routing for multihop wireless networks with renewable energy sources," IEEE/ACM ToN, 2007.
  - Offline scheduling policies
    M.A. Antepli, E. Uysal-Biyikoglu,H. Erkal, "Optimal packet scheduling on an energy harvesting broadcast link," IEEE JSAC, 29(8), 2011.
  - Online scheduling policies
    Z. Wang, A. Tajer, Xiaodong Wang, "Communication of energy harvesting tags," IEEE TCOM, 60(4), 2012.

Contribution

Observation

EH processes are often correlated.

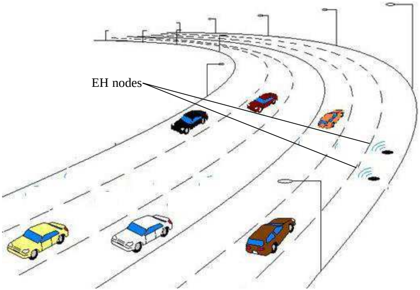


Figure: EH processes with high positive correlation.

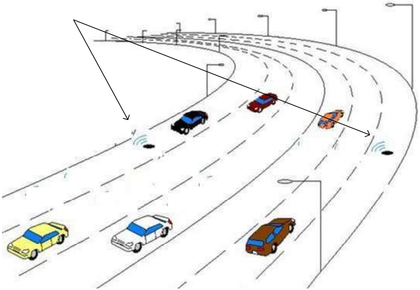


Figure: EH processes with no correlation.

Main Results

Can this knowledge help in coordinating the transmissions?

Main Results

- Develop and analyze a threshold based transmission policy for two EH nodes transmitting to a common destination.
  - Transmit only when battery state exceeds a given threshold value.
  - Threshold is based on the level of correlation between EH processes.
- Thresholds strongly depend on the level of correlation.

System Model

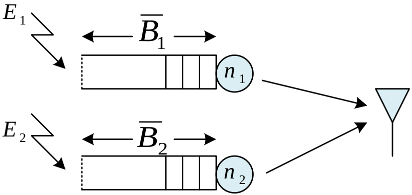


Figure: System Model

- Two nodes uplink channel.
- Contention channel, with simultaneous transmissions resulting in collisions.
- $E_n(t) \in \{0,1\}$, energy harvested by EH node $n = 1,2$ at time slot t is a correlated Bernoulli process.
  - $\Pr(E_1(t) = e_1, E_2(t) = e_2) \neq \Pr(E_1(t) = e_1)\Pr(E_2(t) = e_2)$
- Batteries are of finite size.

Transmission Policy

- Deterministic: Access the channel if the battery level is above a threshold γ_n.
  - No coordination.
  - No feedback.
- Transmit with all the energy in the battery.
- May suffer from collisions.

Let $R_n(t)$ be the rate of *successful* transmissions, i.e.,

$$R_1(t) = \log\left(1 + \frac{B_1(t)/\varepsilon}{N}\right) \mathbb{1}_{\{B_1(t) \geq \gamma_1, B_2(t) < \gamma_2\}},$$
$$R_2(t) = \log\left(1 + \frac{B_2(t)/\varepsilon}{N}\right) \mathbb{1}_{\{B_1(t) < \gamma_1, B_2(t) \geq \gamma_2\}}.$$

where $\varepsilon \ll 1$ is the transmission duration.

Optimal Aggregate Throughput

Objective

$$\max_{\gamma_1,\gamma_2} \mathsf{E}\left[R_1(t)+R_2(t)\right]$$

$p_{e_1 e_2} = \Pr\left(E_1(t)=e_1, E_2(t)=e_2\right),\ e_1,e_2 \in \{0,1\}.$

Theorem

The steady state distribution of DTMC associated with the joint battery state of EH nodes for $p_{01}, p_{10} \neq 0$ *is* $\pi(i,\ j) = \frac{1}{\gamma_1\gamma_2}$, *for* $i = 0,\ldots,\gamma_1 - 1$ *and* $j = 0,\ldots,\gamma_2 - 1$.

Note that Discrete-Time Markov Chain (DTMC) has a product form stationary distribution iff all the states are visited.

Optimal Aggregate Throughput

Tradeoff

- Rate is a concave function of thresholds γ_1, γ_2.
  - Better to transmit small packets frequently, i.e., small γ_1, γ_2.
- Small and frequent transmissions suffer from collisions.
  - Better to transmit large packets only rarely.

- The optimization problem is non-convex.
- A numerical solution is not always possible.

Extreme Special Cases

- Both EH devices are acting oppositely (one at tidal troughs, the other at the crest), i.e., high negative correlation.
- Both EH devices are spatially close, i.e., high positive correlation.

Special Case: High Negative Correlation

- $p_{00} = p_{11} = 0$, $p_{10} = p$ and $p_{01} = 1 - p$ with $0 < p < 1$.

Aggregate Throughput

$$\frac{\log(1+\gamma_1\delta)}{\gamma_1/p} + \frac{\log(1+\gamma_2\delta)}{\gamma_2/(1-p)},$$

where δ is the noise and transmission time normalized energy harvested per each EH event.

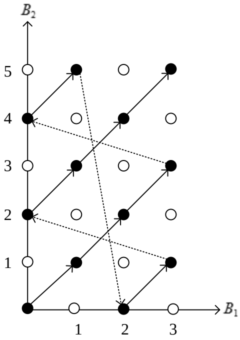
Optimal Thresholds

$\gamma_1 = \gamma_2 = 1$, i.e., each EH device transmits whenever it harvests a single unit of energy.

- The optimal thresholds prevent any collisions between the transmissions of EH devices.

Special Case: High Positive Correlation

- $p_{01} = p_{10} = 0$, $p_{11} = p$ and $p_{00} = 1 - p$ with $0 < p < 1$.
- Only a part of the whole state space of DTMC is visited.
- Example: $\gamma_1 = 4$ and $\gamma_2 = 6$.



Renewal process:

- A collision event every *$LCM(\gamma_1, \gamma_2)$ instances of EH events*.
- After the collision, both nodes exhaust their batteries and visit state $(0, 0)$.

LCM: Least Common Multiple

Special Case: High Positive Correlation

Throughput for EH node n

$$\frac{\frac{LCM(\gamma_1,\ \gamma_2)}{\gamma_n} - 1}{\frac{LCM(\gamma_1,\ \gamma_2)}{p}} \cdot \log(1 + \gamma_n \delta)$$

δ is small:

- Rate term is linear with thresholds.
- Optimum thresholds minimize the number of collisions.
- Choose the thresholds as large as possible as long as $GCD(\gamma_1,\ \gamma_2) = 1$.

δ is large:

- Rate term is concave with respect to thresholds.
- Better to transmit more often using less energy, but this increases colisions.
- Optimal strategy is when one device transmits often whereas the other one only rarely.

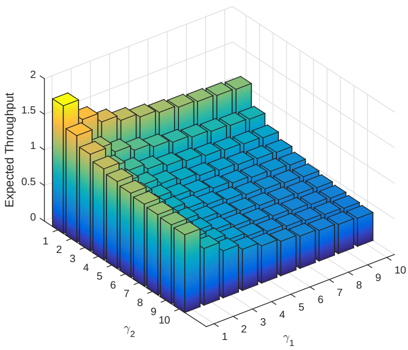
Numerical Results

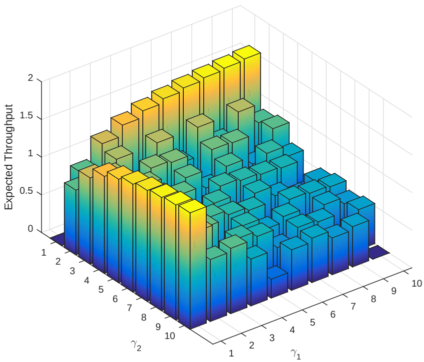
High negative correlation:

- $\bar{B}_1 = \bar{B}_1 = 10.$
- $p = 0.5,\ \delta = 5.$

High positive correlation:

- $\bar{B}_1 = \bar{B}_1 = 10.$
- $p = 0.5,\ \delta = 30.$





Conclusions

- Correlation of EH processes provide a way to coordinate transmissions.
  - A deterministic threshold policy with no coordination and feedback is analyzed.
- In case of high negative correlation, optimal to transmit whenever a node harvests a unit of energy.
- In case of high positive correlation, collisions cannot be avoided without feedback.
  - Choose thresholds balancing the number of collisions and logarithmic transmission rate.
- Generalization of results to more than two nodes, and to other transmission policies taking into account feedback should be investigated.

Thank You!

Appendix

- Noise and transmission time normalized harvested energy.
  - Noise floor = -100dBm.
  - Zigbee transmission rate = 250kbps.
  - Packet size = 133 bytes.