Design, Analysis and Optimization of Energy Harvesting Based Communications

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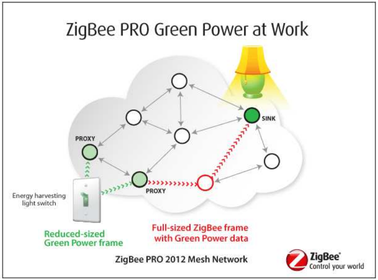
Outline

- Motivation
- System Model
- PDP Analysis
- Optimal SoC-unaware Policies
- Simulation Results
- Future Work



Motivation

- EH technology presents prospects of perpetual operation
- Energy is garnered from ambience for eg. solar, wind etc
- Energy availability is *sporadic*
- Energy buffer (eg. battery) is used to mitigate the sporadicity
- *Energy neutrality constraint*: Cumulative energy used cannot exceed the total harvested energy

Energy Management Policies

- Central issue: design of energy management policies to optimize a utility function
- Policy: prescription of the transmit power on the basis of available system-state information
- Performance depends on the accuracy of the system-state information
- System-state components of EH based communication system
  - State of charge (SoC) of the battery
  - Channel state information (CSI)
- Accurate SoC measurement is difficult [Testa et al., ISIT 2014]

Impact of Inaccurate SoC Information

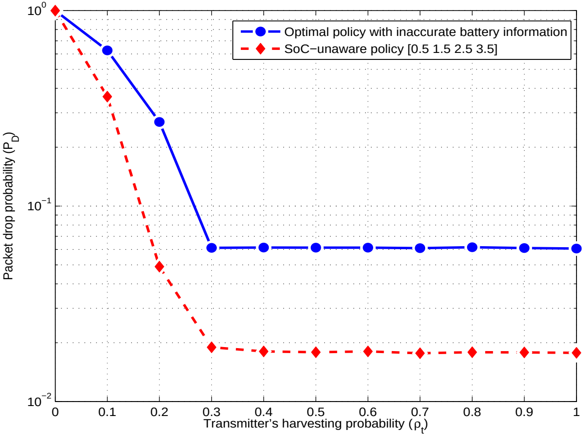
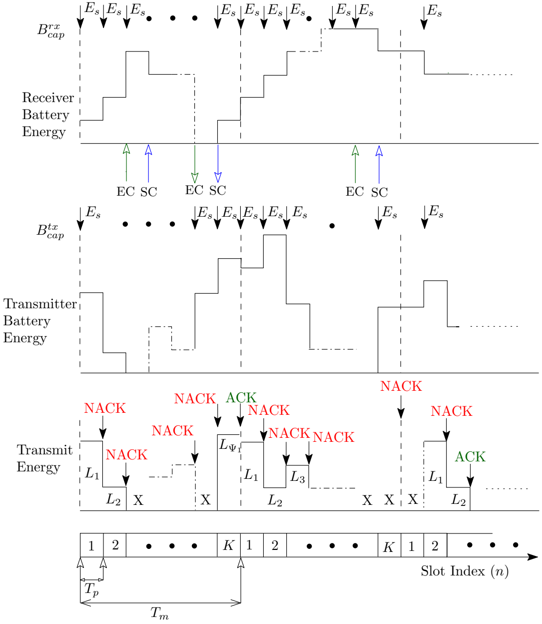


Figure : Performance of optimal battery-aware policy under SoC estimation error. The root-mean-square and the maximum error in the SoC estimation are 5% and 30%, respectively.

Reciever

- Energy Source
  - Generally, receiver is assumed to be connected to mains [Zhang et al., TSP 2012, Ozel et al., JSAC 2011, Anup et al., JSTSP 2013]
  - For full EH networks, deployed for distributed processing and data relaying applications, EH receiver is required
- Data Processing
  - In [Bhargav et al., Globecomm 2009, Anup et al., JSTSP 2013] an ARQ based retransmission scheme is considered
  - Erroneously received packet is discarded
  - For HARQ-CC, the receiver uses all the copies of the packet received so far

System Dynamics



Coordinated Sleep-Wake Protocol

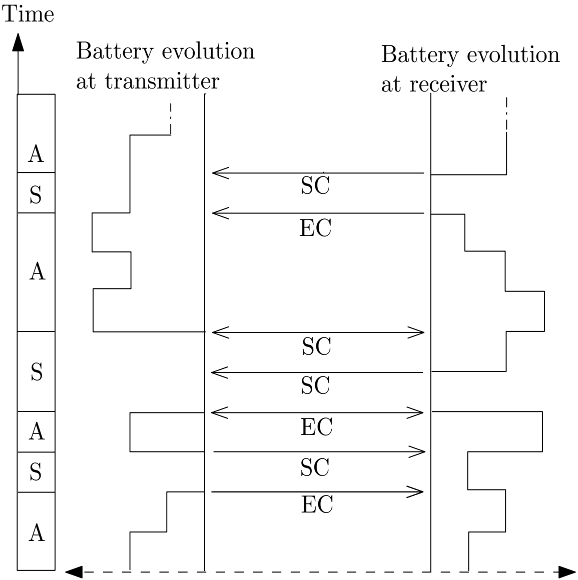


Figure : Coordinated sleep-wake protocol, A: Awake and S: Sleep

Accomplishments

- Packet drop probability (PDP) of dual EH links is analyzed
- Closed-form expressions for the PDP of both ARQ and HARQ-CC are obtained
- Using closed-form expressions we obtained PDP optimal SoC-unaware policies
- Both slow and fast fading channels are considered
- Results for mono EH links are special case of results obtained

Transmit Policy and Battery Evolution

- EHN transmits at predetermined energy levels

$$\{P_1 T_p \triangleq L_1 E_s, P_2 T_p \triangleq L_2 E_s, \ldots, P_K T_p \triangleq L_K E_s\}$$

P_ℓ :Transmit power level in ℓ^{th} attempt

- Tx EHN's battery evolves as

$$B^{\text{tx}}_{n+1} = \begin{cases} \min(B^{\text{tx}}_n + E_s - L_\ell E_s, B^{\text{tx}}_{\text{cap}}), & \text{w.p. } \rho_t \\ B^{\text{tx}}_n - L_\ell E_s, & \text{w.p. } 1 - \rho_t \end{cases}$$

B^{tx}_n : Tx EHN's battery level in n^{th} slot

B^{tx}_{cap} : Tx EHN's battery capacity

- Rx node consumes $P_r T_p = RE_s$ units of power to receive and decode a packet
- Communication happens, if $B^{\text{tx}}_n \geq L_\ell E_s$, and $B^{\text{rx}}_n \geq P_r T_p$

Packet Drop and NACK

- Packet drop: if Tx EHN doesn't receive ACK by the end of the frame
- In ℓ^{th} attempt a NACK is received if

$$\gamma_\ell < \gamma_0$$

where,

γ_ℓ : received SNR

γ_0 : required SNR

- ARQ

$$p_{\text{out}} = \Pr[\gamma_\ell < \gamma_0] = \Pr[P_\ell |h_\ell|^2 < \gamma_0]$$

- HARQ-CC

$$p_{\text{out}} = \Pr[\gamma_{\ell,\text{ac}} < \gamma_0] = \Pr\left[\sum_{i=1}^{\ell} P_i |h_i|^2 < \gamma_0\right]$$

Packet Drop Probability Analysis

- Process evolution, within a frame, is modeled as a discrete time Markov chain
- State of this DTMC: $(B_n^{\text{tx}}, B_n^{\text{rx}}, U_n)$
- Feedback state: $U_n \in \{-1, 0, 1, \ldots, (K-1)\}$:

$$U_n = \begin{cases} -1 & \text{ACK received} \\ 0 & \text{Start of transmission} \\ i & i \text{ NACKs received, } i \in \{1, \ldots, K\} \end{cases}$$

Packet is dropped if and only if $U_K \neq -1$

Packet Drop Probability Analysis

Packet drop probability is

$$P_{\mathrm{D}}(K) = \sum_{i,j} \pi(i,j) P_{\mathrm{D}}(K|i,j,r=0)$$

$\pi(i,j)$: stationary probability that EHNs have (iE_s, jE_s) energy

$$\pi(i_2,j_2) = \sum_{(i_1,j_1)} \Pr\left[(B_{n+1}^{\mathrm{tx}} = i_2, B_{n+1}^{\mathrm{rx}} = j_2)|(B_n^{\mathrm{tx}} = i_1, B_n^{\mathrm{rx}} = j_1)\right] \pi(i_1,j_1)$$

$$\begin{aligned} P_{\mathrm{D}}(K|i,j,r=0) &= \sum_{m_t=0}^{K} \sum_{m_r=0}^{K} \binom{K}{m_t} \binom{K}{m_r} \rho_t^{m_t} \rho_r^{m_r} (1-\rho_t)^{K-m_t} \\ &\quad (1-\rho_r)^{K-m_r} p_{\mathrm{D}}(i,j,m_t,m_r) \end{aligned}$$

$p_D(i, j, m_t, m_r)$ for ARQ

- Slow fading ($T_c = T_m$)

$$\begin{aligned} p_{\text{D}}(i, j, m_t, m_r) &= \Pr\left\{ \bigcap_{\ell=1}^{\Psi_1} \left(|h|^2 < \frac{\gamma_0 \mathcal{N}_0}{P_\ell} \right) \right\} \\ &= \Pr\left\{ \left(|h|^2 < \frac{\gamma_0 \mathcal{N}_0}{P_{\Psi_1}} \right) \right\} = p_{\text{out}}(P_{\Psi_1}) \\ \Psi_1 &= \min\{K, \kappa_t, \kappa_r\} \\ \kappa_t &= \max\{k_i | E_{\text{avl}}^{\text{tx}} - \sum_{k=1}^{k_i} P_k T_p \geq 0\} \\ \kappa_r &= \max\{k_j | E_{\text{avl}}^{\text{tx}} - k_j P_r T_p \geq 0\} \end{aligned}$$

- $E_{\text{avl}}^{\text{tx}} \approx \min\{i + m_t, B_{\text{cap}}^{\text{tx}}\}$ and $E_{\text{avl}}^{\text{tx}} \approx \min\{j + m_r, B_{\text{cap}}^{\text{rx}}\}$
- Fast fading ($T_c = T_p$)

$$p_{\text{D}}(i, j, m_t, m_r) = \prod_{\ell=1}^{\Psi_1} p_{\text{out}}(P_\ell)$$

$p_D(i, j, m_t, m_r)$ for HARQ-CC

- Slow fading

$$p_{\mathrm{D}}(i, j, m_t, m_r) = \Pr\left[|h|^2 < \frac{\gamma_0 \mathcal{N}_0}{\sum_{n=1}^{\Psi_1} P_n}\right] = 1 - e^{-\frac{\gamma_0 \mathcal{N}_0}{\sigma_c^2 \sum_{n=1}^{\Psi_1} P_n}}$$

- Fast fading: using a result in [Misra ITR Dec1997]

$$p_{\mathrm{D}}(i, j, m_t, m_r) = \Pr\left[\sum_{n=1}^{\Psi_1} L_n |h_n|^2 < \frac{\gamma_0 \mathcal{N}_0 T_p}{E_s}\right]$$

$$= 1 - \left(\prod_{j=1}^{a} \beta_j^{r_j}\right) \sum_{k=1}^{a} \sum_{\ell=1}^{r_k} C_{k,\ell}(-\beta_k) \frac{\left(\frac{\gamma_0 \mathcal{N}_0 T_p}{E_s}\right)^{r_k - 1} e^{-\beta_k \frac{\gamma_0 \mathcal{N}_0 T_p}{E_s}}}{(r_k - \ell)!(\ell - 1)!}$$

for a distinct $L_i = \frac{1}{\beta_i}$, and $\sum_{i=1}^{a} r_i = \Psi_1$, and $r_i \geq 1$

Simulation Results: Slow Fading

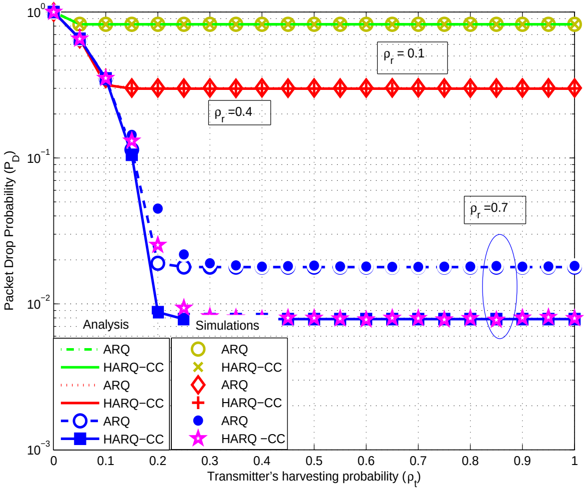


Figure : Slow fading channel: Comparison of analytical expressions and simulations. The parameters chosen are $E_s = 12$ dB, $\gamma_0 = 10$ dB, $K = 4$, $P_r = 2$. The transmission policy used is [0.5 1.5 2.5 3.5].

Simulation Results: Fast Fading

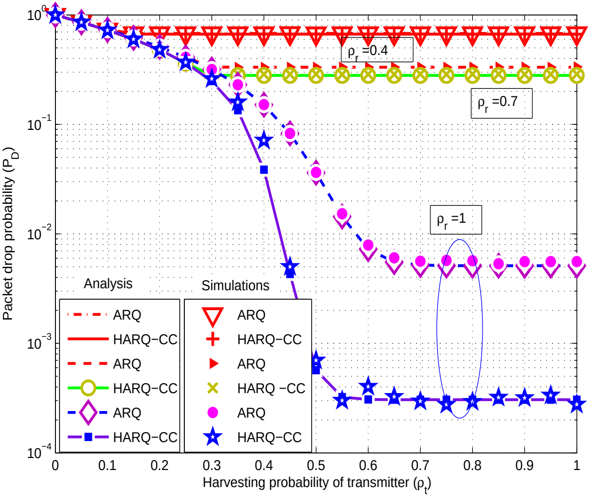


Figure : Fast fading channel: Comparison of analytical expressions and simulations. The parameters chosen are $E_s = 5$ dB, $\gamma_0 = 12$ dB, $K = 4$, $P_r = 2$. The transmission policy used is [0.5 1.5 2.5 3.5].

Harvesting Unconstrained Regime

- Slow Fading: Tx and Rx operates in HUR

$$\begin{aligned}\frac{1}{K}\sum_{t=1}^{K} L_t p_{\text{out}}(L_{t-1}) &< \rho_t \\ \frac{R}{K}\sum_{t=1}^{K} p_{\text{out}}(L_{t-1}) &< \rho_r\end{aligned}$$

- Fast Fading: For Tx and Rx operates in HUR

$$\begin{aligned}\frac{1}{K}\sum_{t=1}^{K} L_t \prod_{p=1}^{t-1} p_{\text{out}}(L_p) &< \rho_t \\ \frac{R}{K}\sum_{t=1}^{K} \prod_{p=1}^{t-1} p_{\text{out}}(L_p) &< \rho_r\end{aligned}$$

- HUR characterization is valid only for *infinite energy buffer*

HUR: Finite Battery

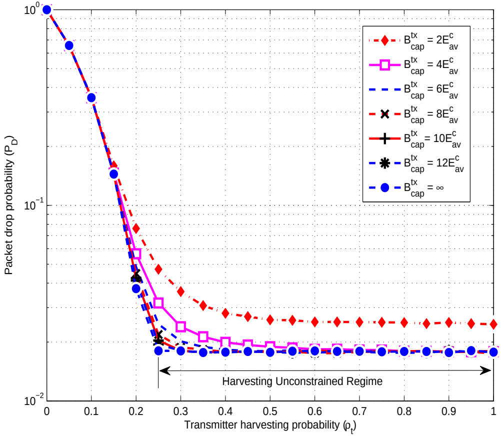


Figure : Harvesting Unconstrained Regime achievability of the ARQ based EH link, with finite energy buffer for slow fading channel. The average energy consumed per frame is, $E^c_{av} \approx 2.4E_s$. The transmission policy used is [0.5 1.5 2.5 3.5]. The parameters chosen are $\gamma_0 = 10$dB, $E_s = 15$ dB, and $K = 4$.

SoC-unaware Optimal Policies

$$\min_{\{P_1,\ldots,P_K\}} \sum_{i=0}^{B_{\text{cap}}^{\text{tx}}} \pi(i) P_{\text{D}}\left(K|i, r=0\right)$$

Lemma 1

The packet drop probability P_{D} is minimized if and only if each $P_{\text{D}}(K|i, r=0)$ is minimum for all i

We have

$$P_{\text{D}}\left(K|i, r=0\right) = \sum_{m=0}^{K} \binom{K}{m} \rho_t^m (1-\rho_t)^{K-m} p_{\text{D}}(i, m)$$

For links operating in HUR: minimize $p_{\text{D}}(i, m)$

Convexity of $p_D(i, m)$ for Fast Fading

Lemma 2

For ARQ with i.i.d. fast fading channels, if $P_n \geq \frac{\gamma_0 \mathcal{N}_0}{2\sigma_c^2}$, for all $1 \leq n \leq K$, then

$$p_D(i, m) = \prod_{\ell=1}^{K} p_{\text{out}}(P_\ell)$$

$$\text{s.t.} \quad \sum_{n=1}^{K} P_n = P$$

is convex in the domain of HUR achieving policies.

Lemma 3

An EH communication link, operating in HUR s.t. $\sum_{i=1}^{K} P_i = P$

1. For basic ARQ with i.i.d. fast fading channel, and $P_i \geq \frac{\gamma_0 \mathcal{N}_0}{2\sigma_c^2}$ for all $1 \leq i \leq K$, then

$$\min_{\{P_1,\ldots,P_K\}} \left\{ \prod_{\ell=1}^{K} P_{\text{out}}(P_\ell) \right\} = \left(P_{\text{out}} \left(\frac{P}{K} \right) \right)^K$$

2. For HARQ-CC with i.i.d slow fading channels

$$\min_{\{P_1,\ldots,P_K\}} \Pr \left[|h_n|^2 < \frac{\gamma_0 \mathcal{N}_0}{\sum_{n=1}^{K} P_n} \right] = \max_{\{P_1,\ldots,P_K\}} \Pr \left[|h_n|^2 < \frac{\gamma_0 \mathcal{N}_0}{\sum_{n=1}^{K} P_n} \right]$$

3. For HARQ-CC with i.i.d fast fading channels, and $\min P_i \geq \frac{\gamma_0 \mathcal{N}_0}{2(K+1)\sigma_c^2}$

$$\min_{\{P_1,\ldots,P_K\}} \Pr \left[\sum_{n=1}^{K} L_n |h_n|^2 < \frac{\gamma_0 \mathcal{N}_0 T_p}{E_s} \right] = \Pr \left[\sum_{n=1}^{K} |h_n|^2 < \frac{\gamma_0 \mathcal{N}_0 T_p K}{P} \right]$$

Optimality of EPTS

Theorem

For an EH communication link, operating in HUR, in the following cases it is optimal to transmit at equal power across all the attempts

1. Basic ARQ on i.i.d. fast fading channels
2. HARQ-CC on slow fading channels
3. HARQ-CC on fast fading channels

Optimality of EPTS

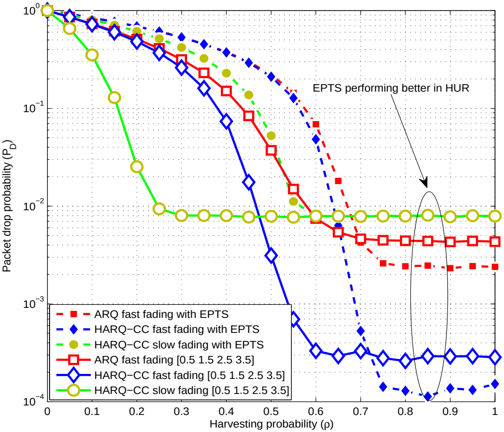


Figure : Optimality of equal power transmission schemes in HUR: Performance comparison of EPTS [2 2 2 2] and [0.5 1.5 2.5 3.5], for a mono EH link.

Conclusion

- Analyzed the PDP of the dual EH links
- For mono EH links the results can be obtained as a special case of the results presented
- Obtained the optimal SoC-unaware policies

Publications

Conference

1. Mohit K. Sharma and Chandra R. Murthy, Packet Drop Probability Analysis of ARQ and HARQ-CC with Energy Harvesting Transmitters and Receivers, Submitted to GlobalSIP 2014.
2. Adithya M. Devraj, Mohit K. Sharma and Chandra R. Murthy, Power Allocation in Energy Harvesting Sensors with ARQ: A Convex Optimization Approach, Submitted to GlobalSIP 2014.

Journal

1. Mohit K. Sharma and Chandra R. Murthy, Design and Analysis of State-of-Charge Unaware Policies for Energy Harvesting Communication, (under preparation)

Future Work

- Characterize the quality of service (QoS) performance limits of EH networks, given a physical layer EH infrastructure

- Joint scheduling for multiple QoS constraints etc