Power Management in Wireless Energy Harvesting Sensors with Retransmissions

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July 27, 2013

Outline

1. Introduction
2. System Model
3. Heuristic Policies
4. Harvesting Optimized Fixed Energy Transmission Scheme
5. Decision Theoretic Policies
6. Conclusions
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Energy Harvesting Sensors (EHS)

- Why use EHS?
  - Operate using the energy they harvest from the environment
  - Capacity to operate for an infinite duration
  - When battery replacement is a hard task
- Problems?
  - Harvesting process is sporadic and unreliable

Objectives

1. Explore various heuristic policies
    - How? Vary transmission energy based on:
        - The present battery energy level
        - Number of ACK's/NAK's received
        - The retransmission index
2. Find the cost of not having channel state information (CSI)
    - Completely observable case vs partially observable case

System Model

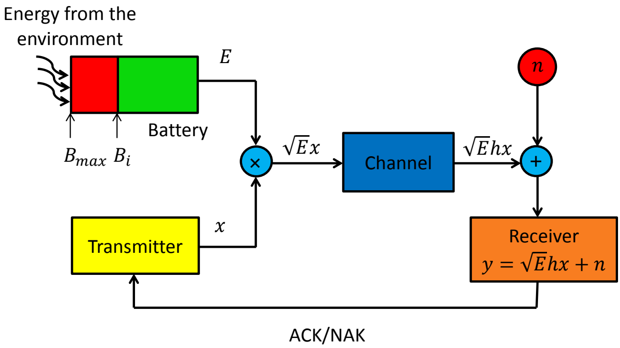

Figure : System model.

System Description

- Transmitter
  - BPSK modulation was used
  - One frame duration is dedicated for transmission of one packet
  - Each frame has K slots
    - Transmitter has K attempts in each frame to successfully transmit a packet
  - If packet is not successfully transmitted in one frame?
    - Discard the packet; Outage is said to occur
- Energy Injection Process
  - Every slot, E_s energy is harvested with prob. ρ and no energy is harvested with prob. $1 - \rho$

- Channel
  - Modelled as a finite state Markov chain (FSMC) [3]
- Packet error probability:

$$P_e(E_i, \gamma) = 1 - \left(1 - Q\left(\sqrt{\frac{2\gamma E_i}{N_0}}\right)\right)^L \quad (1)$$

- Feedback:
  - If packet is in error: (NAK) is sent
  - If packet is successfully decoded: (ACK) is sent
- Performance metric:

$$\text{Outage probability} = \frac{\text{number of packets discarded}}{\text{number of frames}} \quad (2)$$

Transmission Timeline

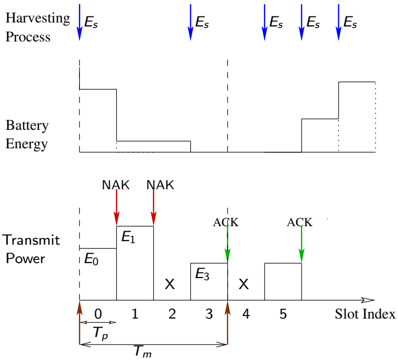

Figure : Transmission timeline of the EH node for $K = 4$, showing the random energy harvesting process $(\downarrow)$ and periodic data arrival $(\uparrow)$.The marker "X" denotes slots where the EHS does not transmit data

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Heuristic Policies

- First, simulated the fixed energy transmission scheme:
  - Transmit at different fixed energies $E = W \times E_s$
- $K = 4$, $N_0 = 1mJ$ and $E_s = 1mJ$ ($0dB$ with respect to N_0)
- Finite battery capacity $B_{\text{max}} = 20E_s$
- 7 state FSMC channel with $f_m T_p = 0.03$ was used
- Outage probability vs ρ was plotted

Fixed Energy Transmission Scheme

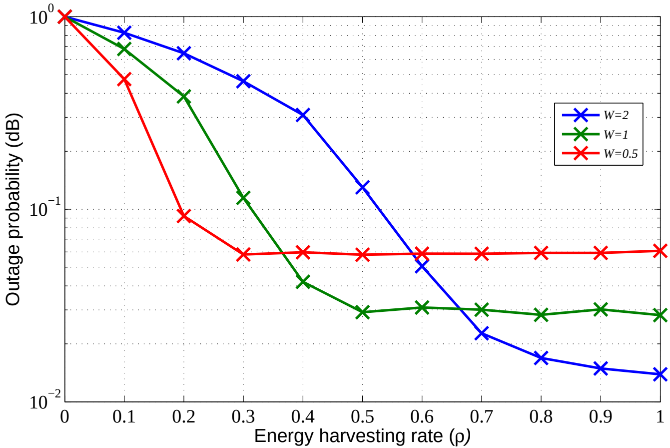

Figure : Plot of outage probability versus energy harvesting rate using fixed energy transmission scheme, for different values of $W = E/E_s$.

Battery State and ACK/NAK Threshold Policy

- First, transmit with initial energy E
- If ACK is received, and if battery energy level, $B_i \leq 4E$
  - Transmission energy is decreased by $0.5mJ$
  - The energy should not decrease below $0.5mJ$
- If an NAK is received:
  - If$(B_i \leq 5E_{tx})$, don't change E_{tx}
  - If $(5E_{tx} < B_i \leq 10E_{tx})$ then increase E_{tx} by $2mJ$ $(E_{tx} = E_{tx} + 2mJ)$
  - Similarly, if $(10E_{tx} < B_i \leq 15E_{tx})$ then E_{tx} is increased by $4mJ$ $(E_{tx} = E_{tx} + 4mJ)$
  - And, if $(15E_{tx} < B_i)$ then E_{tx} is increased by $8mJ$ $(E_{tx} = E_{tx} + 8mJ)$
- At the K^{th} slot, if ACK is not received, transmit with all the energy in the battery

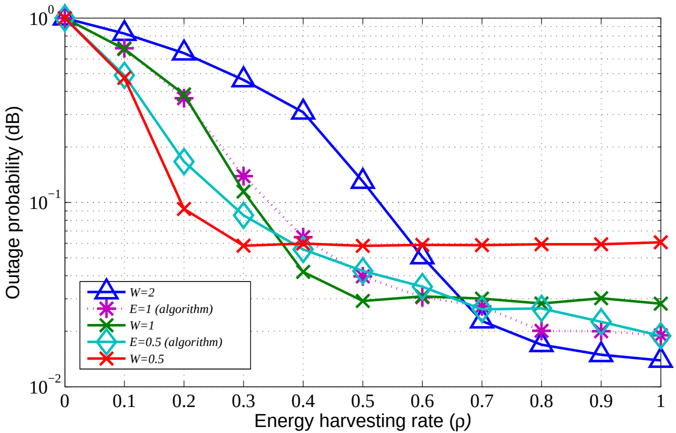

Figure : Energy harvesting rate(ρ) vs outage probability graph using the Heuristic Threshold Policy.

Policy Using the Energy Harvesting Rate ρ

- Different policies did well at different ρ values
- Make transmission energy a function of ρ

$$E_{tx} = f(\rho)$$

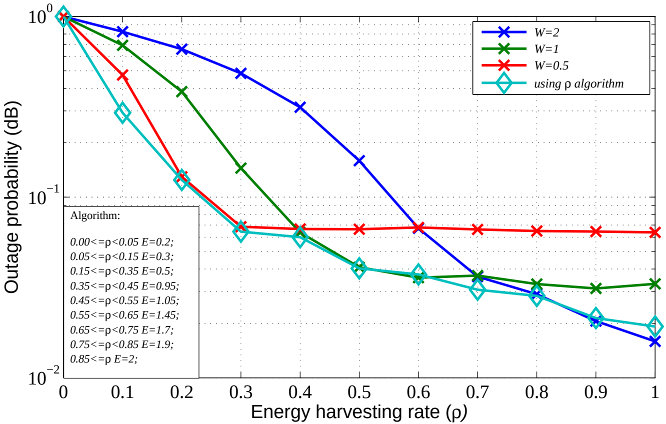

Figure : Energy harvesting rate(ρ) vs outage probability graph taking the energy harvesting rate (ρ) into consideration.

Harvesting Optimized Fixed Energy Transmission Scheme

- Here,

$$E_{tx} = \epsilon K \rho E_s \tag{3}$$

- Objective, to minimize the outage:

$$P_{out} = P_e^K(\epsilon K \rho E_s, \gamma) \tag{4}$$

- Average energy harvested per frame:

$$\bar{E_s} = K \rho E_s \tag{5}$$

- Average energy used per frame using energy E_{tx}:

$$\begin{aligned}\bar{E_{tx}} = \mathbb{E}_\gamma\{&\epsilon K \rho E_s(1 - P_e(\epsilon K \rho E_s, \gamma)) \\ &+2\epsilon K \rho E_s(P_e(\epsilon K \rho E_s, \gamma))(1 - P_e(\epsilon K \rho E_s, \gamma)) \\ &+ \ldots + (K-1)\epsilon K \rho E_s(P_e(\epsilon K \rho E_s, \gamma))^{K-2}(1 - P_e(\epsilon K \rho E_s, \gamma)) \\ &+K^2 \epsilon \rho E_s(P_e(\epsilon K \rho E_s, \gamma))^{K-1}\}\end{aligned} \tag{6}$$

- Energy unconstrained regime occurs when $\bar{E_{tx}} \leq \bar{E_s}$:

$$\begin{aligned}
&\mathbb{E}_\gamma\{\epsilon K\rho E_s(1 - P_e(\epsilon K\rho E_s,\gamma)) \\
&\quad +2\epsilon K\rho E_s(P_e(\epsilon K\rho E_s,\gamma))(1 - P_e(\epsilon K\rho E_s,\gamma)) \\
&\quad +\ldots+(K-1)\epsilon K\rho E_s(P_e(\epsilon K\rho E_s,\gamma))^{K-2}(1 - P_e(\epsilon K\rho E_s,\gamma)) \\
&\quad +K\epsilon K\rho E_s(P_e(\epsilon K\rho E_s,\gamma))^{K-1}\} \leq K\rho E_s
\end{aligned} \tag{7}$$

- Find optimum ϵ satisfying (7) and minimizing (4)

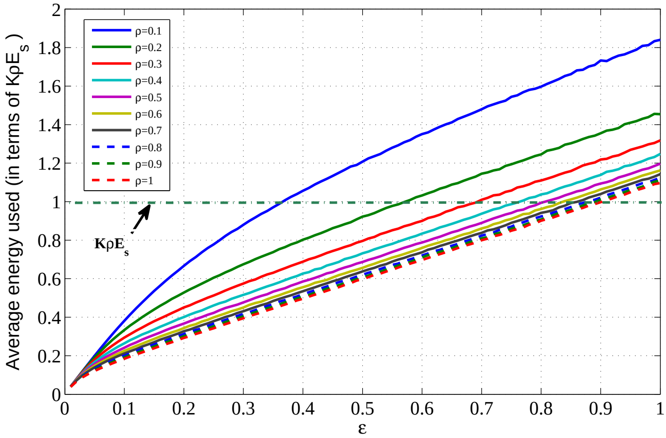

Figure : ϵ vs average energy used (given by equation (6)) for an IID channel and $E_s = 12dB$. Notice that average energy used per frame crosses $K\rho E_s$ for $\epsilon < 1$.

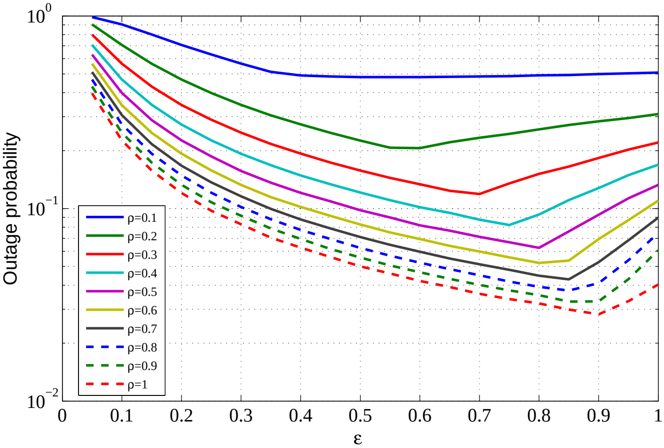

Figure : ϵ vs outage probability (using Monte Carlo simulations) for various values of energy harvesting rate (ρ). Here infinite battery capacity is used.

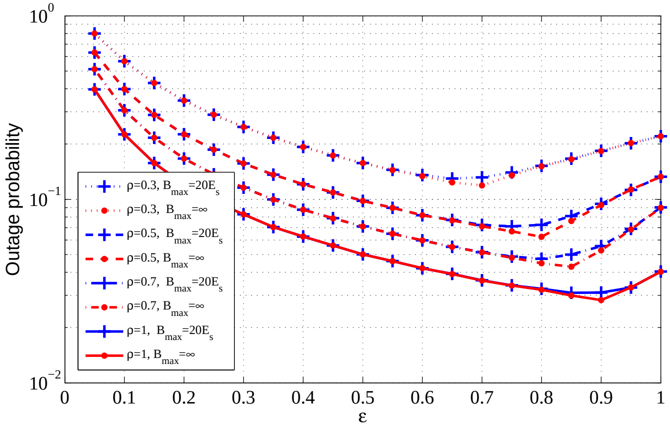

Figure : Comparison of the outage probabilities for finite battery capacity ($B_{\max} = 20E_s$) and infinite battery capacity for different values of ϵ and energy harvesting rates.

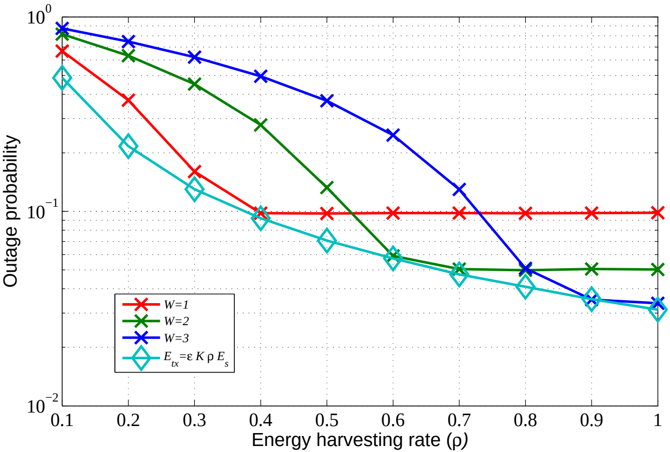

Figure : Energy harvesting rate (ρ) vs outage probability using the Harvesting Optimized Fixed Energy Transmission Scheme.

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Basic Structure of MDP

An MDP consists of

- A set of states
- A set of actions
- A transition probability function
- A reward function

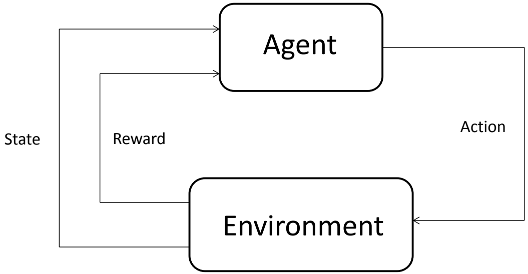

Figure : Basic block diagram of MDP

- Policy π
  - Mapping from state space to action space $\mathbb{S} \rightarrow \mathbb{A}$
- Value Function $V(s)$
  - Expected discounted reward starting from some state s

$$V_\pi(s) = R(s, \pi(s)) + \nu \sum_{s' \in S} T(s, \pi(s), s') V_\pi(s') \tag{8}$$

- Objective: To find an optimal policy π^* which maximises $V(s)$

Value Iteration Algorithm

- Used to solve MDP
- Value iteration algorithm is as follows:

$V_1(s) = 0$ for all s

t=1

begin loop

t=t+1

begin loop for all $s \in S$

    begin loop for all $a \in A$

$$Q_t^a(s) = R(s,a) + \gamma \sum_{s' \in S} T(s,a,s') V_{t-1}(s')$$

    end loop

$V_t(s) = \max_a Q_t^a(s)$

end loop

until $|V_t(s) - V_{t-1}(s)| < \epsilon$ for all $s \in S$

Formulation of Our Problem as an MDP

- Our basic idea was to use MDP to sequentially decide the transmission energy (action) based on:
  - the current battery energy level (B_i)
  - the retransmission index (k)
  - the current channel state (γ_i)
  - the energy harvesting rate (ρ)
- All the energies are normalized with respect to $E_{\min}$
- $L = E_s/E_{\min}$ is the normalized energy harvested

State Space

$\mathbb{S} = \mathbb{B} \times \mathbb{G} \times \mathbb{K} \times \mathbb{U}$ consists of the following subspaces

- The set of battery states $\mathbb{B} = \{0, 1, ..., B_{\text{max}}\}$
- The set of channel states $\mathbb{G} = \{\gamma_1, \gamma_2, ..., \gamma_N\}$
- The set of retransmission indices $\mathbb{K} = \{0, 1, ..., K - 1\}$
- The set of packet reception states $\mathbb{U} = \{0, 1\}$
    - 1 when an ACK is received
    - 0 when a NAK is received
    - Set to 0 at the beginning of every frame

Action Space

- Set of possible actions $\mathbb{A} = \{0, 1, ..., b\}, b \in \mathbb{B}$
- Different energies of transmission
- When $a \in \mathbb{A}$ is chosen, transmission energy $E_t = aE_{\text{min}}$

State Transition Probability

- Consider two arbitrary states $s = \{b, \gamma, k, u\}$ and $s' = \{b', \gamma', k', u'\}$ in $\mathbb{S}$
- The state transition probability function is as follows:

$$\mathcal{T}(s, a, s') = \delta(k', k_+)P_{\gamma,\gamma'}\psi((b, u), a, (b', u'), k, \gamma) \tag{9}$$

  - $k_+ = (k + 1) \bmod K$
  - $\delta\{k', k\}$ = Kronecker delta function
  - $P_{\gamma,\gamma'}$ = transition probability of the channel state from γ to γ'
  - $\psi((b, u), a, (b', u'), k, \gamma)$ = probability that the system starts from battery state b and packet reception state u, takes an action a, and lands in the state (b', u')

- Let

$$\eta(b,a,b') = \rho\delta(b', \min(b+L-a, B_{\max})) + (1-\rho)\delta(b', b-a) \quad (10)$$

- If $k = K-1$,

$$\psi((b,u),a,(b',u'),k,\gamma) = \begin{cases} \eta(b,a,b') & \text{when } u' = 0 \\ 0 & \text{otherwise.} \end{cases} \quad (11)$$

- If $k \neq K-1$,

$$\psi((b,u),a,(b',u'),k,\gamma) = \begin{cases} \eta(b,a,b') & u' = 1, u = 1 \\ \eta(b,a,b')(1 - P_e(aE;\gamma)) & u' = 1, u = 0 \\ \eta(b,a,b')P_e(aE;\gamma) & u' = 0, u = 0 \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

Reward

- Let $s = (b, \gamma, k, u)$ be the state of the system. The expected reward is defined as

$$\mathcal{R}(s, a) = \begin{cases} 1 - P_e(aE; \gamma) & a \leq b, u = 0 \\ -10 & (a > b, u = 0) \text{ or } (a \neq 0, u = 1) \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

Solution to the MDP

- Solution to the MDP is an optimal policy μ^*_{MDP}
  - Mapping from state space $\mathbb{S}$ to action space $\mathbb{A}$
- Obtained by finding the solution to the Bellman equation:

$$\lambda^* + h^*(s) = \max_{a \in \mathbb{A}, a \leq \mathbb{B}(s)} \left[\mathcal{R}(s,a) + \nu \sum_{s' \in \mathbb{S}} \mathcal{T}(s,a,s') h^*(s') \right] \tag{14}$$

  - ν: Discount factor
  - λ^*: Optimal average reward
  - h^*: Optimal reward vector

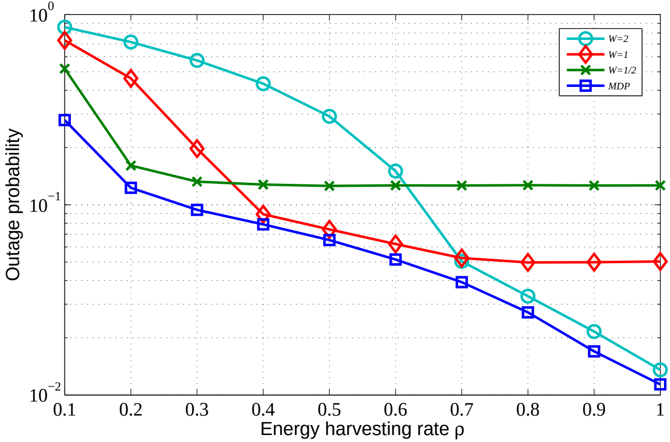

Figure : Energy harvesting rate(ρ) vs outage probability graph for policy using MDP. Here, normalized Doppler $(f_m T_p)$=0.001, $K = 3$, $E_s = 12dB$, $B_{\max} = 10E_s$, $E_{\min} = 0.25Es$, $N_0 = 1$

General Performance Comparison With the Case of Partial Observability

- Suppose exact CSI is unknown at the Rx:
  - Partially observable Markov decision process (POMDP) can be used [2]
  - Calculate the belief of the channel states $\beta(\gamma)$:

$$\beta_n(\gamma_j) = \frac{\sum_i P_{\gamma_i,\gamma_j} P(o_{n-1}|a_{n-1},\gamma_i)\beta_{n-1}(\gamma_i)}{\sum_j \sum_i P_{\gamma_i,\gamma_j} P(o_{n-1}|a_{n-1},\gamma_i)\beta_{n-1}(\gamma_i)} \quad (15)$$

- $o_n \in \mathbb{O}$ is the observation function: ACK/NAK
- a_n is the action chosen at the n^{th} instant

- Maximum Likelihood (ML) heuristic:

$$\gamma_{\text{ML}} = \arg\max_{\gamma \in \mathbb{G}} \beta(\gamma) \tag{16}$$

$$s_{\text{ML}} = (b, \gamma_{\text{ML}}, k, u) \tag{17}$$

$$\mu_{\text{ML}} = \mu^*_{\text{MDP}}(s_{\text{ML}}) \tag{18}$$

- Voting policy heuristic:

$$\mu_{\text{voting}} = \arg\max_{a \in \mathbb{A}} \sum_{\substack{s=(b,\gamma,k,u) \\ \gamma \in \mathbb{G}}} \beta(s)\delta(\mu^*_{\text{MDP}}(s), a) \tag{19}$$

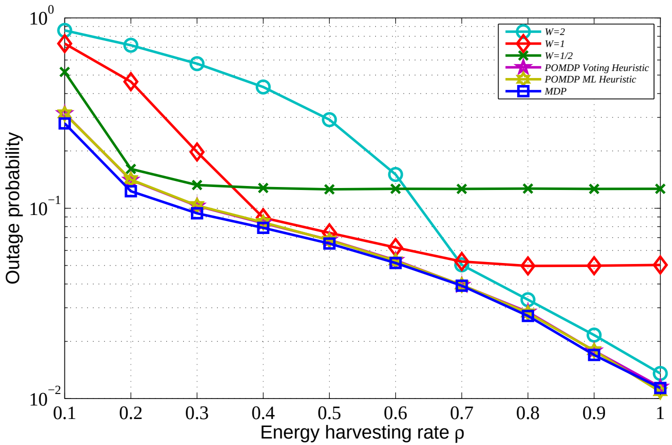

Figure : Energy harvesting rate(ρ) vs outage probability graph for comparison of the performance of MDP and POMDP. Here again, normalized Doppler $(f_m T_p)$=0.001, $K = 3$, $B_{\max} = 10E_s$, $E_{\min} = 0.25Es$, $E_s = 12dB$, $N_0 = 1$

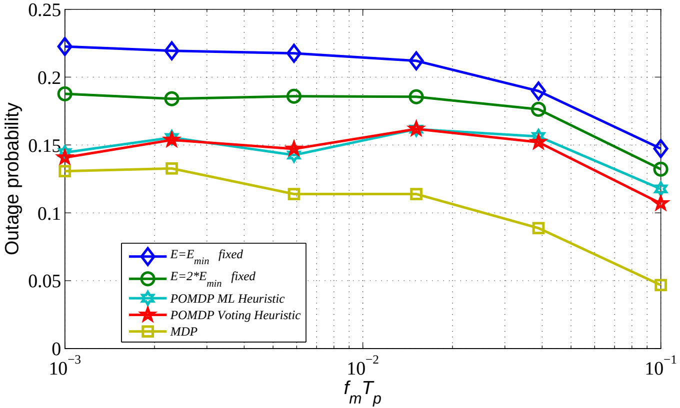

Figure : MDP and POMDP performance comparison for different values of normalized Doppler. Here, $\rho = 0.1$, $K = 3$, $B_{\max} = 5E$, $E_{\min} = 0.25E$, $E_s = 3E$ ($12E_{\min}$) and $N_0 = 1$, where $E = 12dB$ (normalized with respect to N_0)

Formulation of MDP without including the Channel States

- The performance difference between MDP and POMDP is large at higher $f_m T_p$
- Difficult to guess the channel state as fading rate increases
- Instead, formulating an MDP independent of the channel states could do better?

State Space

$\mathbb{S} = \mathbb{B} \times \mathbb{K} \times \mathbb{U}$ consists of the following subspaces

- The set of battery states $\mathbb{B} = \{0, 1, ..., B_{\text{max}}\}$
- The set of retransmission indices $\mathbb{K} = \{0, 1, ..., K - 1\}$
- The set of packet reception states $\mathbb{U} = \{0, 1\}$

State Transition Probability

- State transition probability from state $s = \{b, k, u\}$ to $s' = \{b', k', u'\}$ in $\mathbb{S}$ is as follows:

$$\mathcal{T}(s, a, s') = \delta(k', k_{+})\psi((b, u), a, (b', u'), k) \tag{20}$$

  - $k_{+} = (k + 1) \bmod K$
  - $\delta\{k', k\}$ = Kronecker delta function
  - $\psi((b, u), a, (b', u'), k)$ = probability that the system starts from battery state b and packet reception state u, takes an action a, and lands in the state (b', u')

- Let

$$\eta(b, a, b') = \rho\delta(b', \min(b + L - a, B_{\max})) + (1 - \rho)\delta(b', b - a) \quad (21)$$

$$\bar{P}_e(aE) = \mathbb{E}_\gamma\{P_e(aE; \gamma)\} \quad (22)$$

- If $k = K - 1$,

$$\psi((b, u), a, (b', u'), k) = \begin{cases} \eta(b, a, b') & \text{when } u' = 0 \\ 0 & \text{otherwise.} \end{cases} \quad (23)$$

- If $k \neq K - 1$,

$$\psi((b, u), a, (b', u'), k) = \begin{cases} \eta(b, a, b') & u' = 1, u = 1 \\ \eta(b, a, b')(1 - \bar{P}_e(aE)) & u' = 1, u = 0 \\ \eta(b, a, b')\bar{P}_e(aE) & u' = 0, u = 0 \\ 0 & \text{otherwise} \end{cases} \quad (24)$$

Reward

- Let $s = (b, \gamma, k, u)$ be the state of the system. The expected reward is defined as

$$\mathcal{R}(s,a) = \begin{cases} 1 - \bar{P}_e(aE) & a \leq b, u = 0 \\ -10 & (a > b, u = 0) \text{ or } (a \neq 0, u = 1) \\ 0 & \text{otherwise} \end{cases} \tag{25}$$

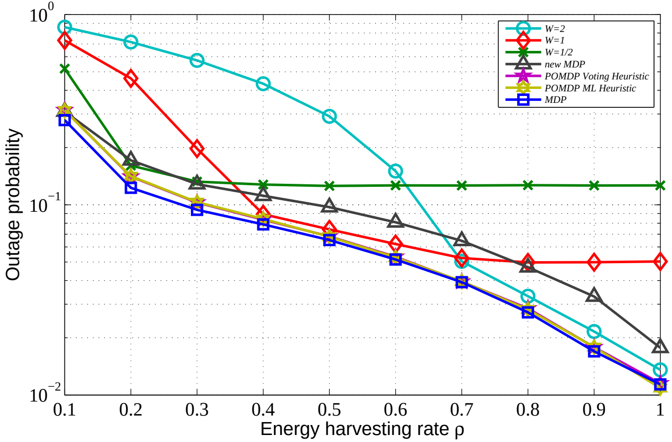

Figure : Energy harvesting rate(ρ) vs outage probability graph to compare policies using MDP, POMDP and new MDP. Here, normalized Doppler $(f_m T_p)$=0.001, $K = 3$, $E_s = 12dB$, $B_{\max} = 10E_s$, $E_{\min} = 0.25Es$, $N_0 = 1$

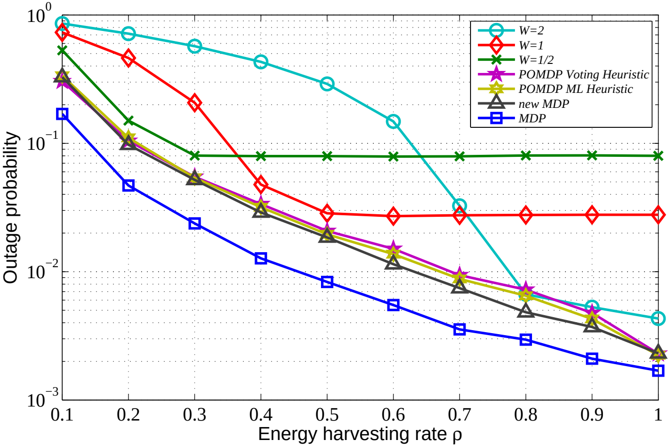

Figure : Energy harvesting rate(ρ) vs outage probability graph for policy using MDP. Here, normalized Doppler $(f_m T_p)$=0.0389, $K = 3$, $E_s = 12dB$, $B_{\max} = 10E_s$, $E_{\min} = 0.25Es$, $N_0 = 1$

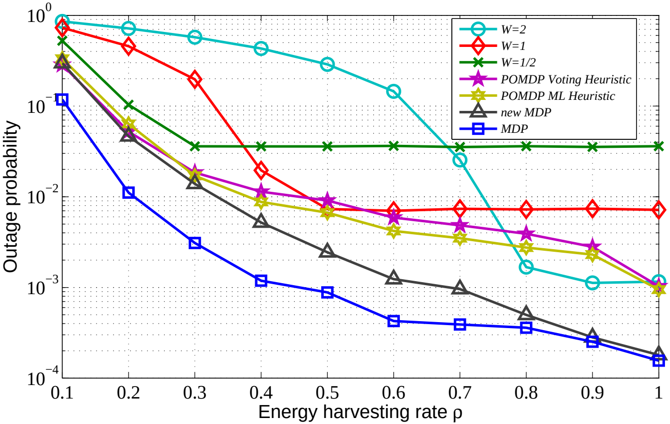

Figure : Energy harvesting rate(ρ) vs outage probability graph for policy using MDP. Here, normalized Doppler $(f_m T_p)$=0.1, $K = 3$, $E_s = 12dB$, $B_{\max} = 10E_s$, $E_{\min} = 0.25Es$, $N_0 = 1$

Conclusions

- Channel dependent MDP performed the best at all scenarios
- The performance of POMDP worsened at higher $f_m T_p$
- Channel independent MDP performed well at higher $f_m T_p$
  - Advantages over POMDP and MDP:
    - Computationally inexpensive
    - Easy implementation
  - Disadvantage
    - Still need to evaluate a policy every time ρ, K, E_s or $B_{\max}$ changes
- The policy with $E_{tx} = \epsilon K \rho E_s$ also gave a good overall performance

Future Work

- Exploit channel correlation:
  - $E_{tx} = f(\rho, ACK/NAK, \delta)$
  - Start with $E_0 = \epsilon_0 K \rho E_s$
  - Update ϵ as:

$$\epsilon_{\text{new}} = \epsilon_{\text{old}} + a \cdot b(\delta)$$

$$a = \begin{cases} -1, & \text{ACK} \\ +1, & \text{NAK} \end{cases}$$

δ : Time duration since the last observation of ACK/NAK

b : Decreasing function of δ

- Applying the Chase combining concept
- Performance analysis in terms of good-put rate

Thank you!

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