Scheduling an Energy harvesting Network

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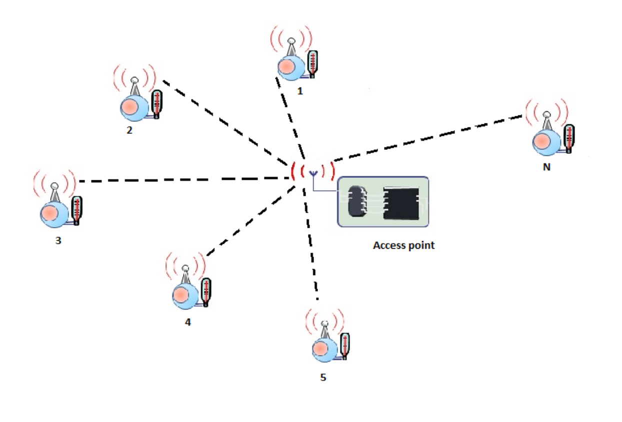
Agenda

- Motivation
- System Model
- Problem statement
- MDP Formulation
- Simulation Results

Motivation

- Cyber-physical system typically employ wireless sensors for keeping track of physical processes such as temperature and pressure. These nodes then transmit data packets containing measurements back to the access point.
- The Time between successive deliveries of packets is an important metric.
- Wireless sensors are battery powered.Thus, energy-efficiency is also important.

System Model



- All 'N' Sensor Nodes are Energy Harvesting sensors.
- Access point(AP) is Powered by External Battery.

Problem statement

- Atmost L(<N) sensors can simultaneously transmit in a time slot.
- A Control message is sent at the beginning by the AP to select L sensors out of N sensors.

A scheduling algorithm for N wireless energy harvesting nodes is to be designed to the following constraints:

- Uniform sized packets arrive at random times at each node(each node has queue associated with it). Each packet has a deadline by which it needs to be delivered.
- The best delivery ratios we can support?

Assumptions:

- Battery state of all the EH sensor nodes is known.
- Packet success probability of all the EH sensor nodes is known.
- The Energy Harvesting Rate of all the nodes is known.
- The Energy required to transmit a packet is 1 unit.
- The Energy Harvested in a given time slot is 1 unit.

MDP Formulation:

Goal: Scheduling the nodes based on the battery energy level, Success Probability and Time elapsed since the latest delivery of the client n's packet.

a) *State space:*
   - $B = \{0, 1, ..., b_{max}\}$ is the set of Battery states. $B(t) := (b_1(t), ..., b_N(t))$, Where $b_n(t)$ is the Battery of client n's in time slot t.
   - $X(t) := (x_1(t), ..., x_N(t))$,Where $x_n(t)$ is the time elapsed since the latest delivery of client n's packet.
   - $O(t) := (o_1(t), ..., o_N(t))$, Where $o_n(t)$ is the Packet reception state of client n's in time slot t.

b) *Action space:* $U(t) := (u_1(t), ..., u_N(t))$, Where $u_n(t)$ is the Action taken for client n, in time slot t.

$$\sum_{n=1}^{N} u_n(t) \leq L \tag{1}$$

Contd.

$$u_n(t) = \begin{cases} 1 \text{ if client } n \text{ is selected to transmit in slot } t \\ 0 \text{ otherwise} \end{cases}$$

c) *State Transition Function:* Let Two arbitrary states in S be $s = (B, X, O)$ and $s' = (B', X', O')$. The state Transition function is the probability that the system starts in state s, takes an action U, and lands in state s'.
The system state evolves as,

$$x_n(t+1) = \begin{cases} 0 \text{ if a packet of client } n \text{ is delivered in } t \\ x_n(t) + 1 \text{ otherwise} \end{cases}$$

$$b_n(t+1) = \begin{cases} min(b_n(t) + 1, b_{n(max)}) \text{ with probability } \rho \text{ of client } n \text{ in } t \\ b_n(t) \text{ with probability } 1 - \rho \text{ of client } n \text{ in } t \end{cases}$$

Contd..

- Considering A small Network consisting of Two EHS nodes and an Access point.
- Scheduling policy: Access point can schedule at the most Only one sensor Node. N=2,L={0,1}

$$B = (b_1, b_2), X = (x_1, x_2), U = (u_1, u_2), O = (o_1, o_2)$$
$$(b_1, b_2, x_1, x_2, o_1, o_2) \xrightarrow{(u_1,u_2)} (b_1', b_2', x_1', x_2', o_1', o_2')$$
$$\text{Possible Action set: } (u_1, u_2) = \{(0,0), (1,0), (0,1)\}$$

- Energy harvesting rate of Node1$=\rho_1$
- Energy harvesting rate of Node2$=\rho_2$
- Success Probability of Node1$=p_1$
- Success Probability of Node2$=p_2$

The State Transition Probability is given by,

$$\psi((B,X,O),U,(B',X',O')) = P((B',X',O')|(B,X,O))$$

$P((B',X',O')|(B,X,O))$
$= P(b_1' = j_1, b_2' = j_2, x_1' = y_1, x_2' = y_2, o_1' = s_1, o_2' = s_2 | b_1 = i_1, b_2 =$
$i_2, x_1, x_2, o_1 = r_1, o_2 = r_2)$

cntd..

$P((B', X', O')|(B, X, O)) =$

Case-1: $U = (u_1 = 0, u_2 = 0)$ None of the Nodes are Scheduled.

- In this case No need to of the observation vector.

$$= \begin{cases} \rho_1\rho_2, & j_1 = min(i_1 + 1, b_{1max}), j_2 = min(i_2 + 1, b_{2max}), y_1 = x_1 + 1, \\ & y_2 = x_2 + 1, \\ (1-\rho_1)\rho_2, & j_1 = i_1, j_2 = min(i_2 + 1, b_{2max}), y_1 = x_1 + 1, y_2 = x_2 + 1, \\ \rho_1(1-\rho_2), & j_1 = min(i_1 + 1, b_{1max}), j_2 = i_2, y_1 = x_1 + 1, y_2 = x_2 + 1, \\ (1-\rho_1)(1-\rho_2), & j_1 = i_1, j_2 = i_2, y_1 = x_1 + 1, y_2 = x_2 + 1, \\ 0, & else. \end{cases}$$

cntd..

Case-2: $U = (u_1 = 1, u_2 = 0)$ Node1 is scheduled.

$$
= \begin{cases}
(1-p_1)\rho_1\rho_2, \; j_1 = min(i_1+1-1, b_{1max}), j_2 = min(i_2+1, b_{2max}), \\
\quad y_1 = x_1+1, y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_1)(1-\rho_1)\rho_2, \; j_1 = max(i_1-1, 0), j_2 = min(i_2+1, b_{2max}), \\
\quad y_1 = x_1+1, y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_1)\rho_1(1-\rho_2), \; (j_1 = min(i_1+1-1, b_{1max}), j_2 = i_2, y_1 = x_1+1, \\
\quad y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_1)(1-\rho_1)(1-\rho_2), \; j_1 = max(i_1-1, 0), j_2 = i_2, y_1 = x_1+1, \\
\quad y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
0, \quad else.
\end{cases}
$$

cntd...

$$
= \begin{cases}
p_1\rho_1\rho_2,\ j_1 = min(i_1+1-1, b_{1max}), j_2 = min(i_2+1, b_{2max}), \\
\qquad y_1 = 0, y_2 = x_2+1, s_1 = 1, s_2 = 0, \\
p_1(1-\rho_1)\rho_2,\ j_1 = max(i_1-1, 0), j_2 = min(i_2+1, b_{2max}), \\
\qquad y_1 = 0, y_2 = x_2+1, s_1 = 1, s_2 = 0, \\
p_1\rho_1(1-\rho_2),\ (j_1 = min(i_1+1-1, b_{1max}), j_2 = i_2, y_1 = 0, \\
\qquad y_2 = x_2+1, s_1 = 1, s_2 = 0, \\
p_1(1-\rho_1)(1-\rho_2),\ j_1 = max(i_1-1, 0), j_2 = i_2, y_1 = 0, y_2 = x_2+1, \\
\qquad s_1 = 1, s_2 = 0, \\
0, \quad else.
\end{cases}
$$

Case-3: $U = (u_1 = 0, u_2 = 1)$ Node2 is scheduled.

$$
= \begin{cases}
(1-p_2)\rho_1\rho_2, \; j_1 = min(i_1+1, b_{1max}), j_2 = min(i_2+1-1, b_{2max}), \\
\qquad y_1 = x_1+1, y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_2)(1-\rho_1)\rho_2, \; j_1 = i_1, j_2 = min(i_2+1-1, b_{2max}), \\
\qquad y_1 = x_1+1, y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_2)\rho_1(1-\rho_2), \; j_1 = min(i_1+1, b_{1max}), j_2 = max(i_2-1, 0), \\
\qquad y_1 = x_1+1, y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
(1-p_2)(1-\rho_1)(1-\rho_2), \; j_1 = i_1, j_2 = max(i_2-1, 0), y_1 = x_1+1, \\
\qquad y_2 = x_2+1, s_1 = 0, s_2 = 0, \\
0, \quad else.
\end{cases}
$$

cntd...

$$
= \begin{cases}
p_2\rho_1\rho_2, \;\; j_1 = min(i_1+1, b_{1max}), j_2 = min(i_2+1-1, b_{2max}), \\
\qquad y_1 = x_1+1, y_2 = 0, s_1 = 0, s_2 = 1, \\
p_2(1-\rho_1)\rho_2, \;\; j_1 = max(i_1-1, 0), j_2 = min(i_2+1, b_{2max}), \\
\qquad y_1 = x_1+1, y_2 = 0, s_1 = 0, s_2 = 1, \\
p_2\rho_1(1-\rho_2), \;\; (j_1 = min(i_1+1-1, b_{1max}), j_2 = i_2, y_1 = x_1+1, \\
\qquad y_2 = 0, s_1 = 0, s_2 = 1, \\
p_2(1-\rho_1)(1-\rho_2), \;\; j_1 = max(i_1-1, 0), j_2 = i_2, y_1 = x_1+1, y_2 = 0, \\
\qquad s_1 = 0, s_2 = 1, \\
0, \qquad else.
\end{cases}
$$

Cost: Let $s = (B, X, O)$ be the state of the system.
The expected immediate cost is defined as,
c(S,U)

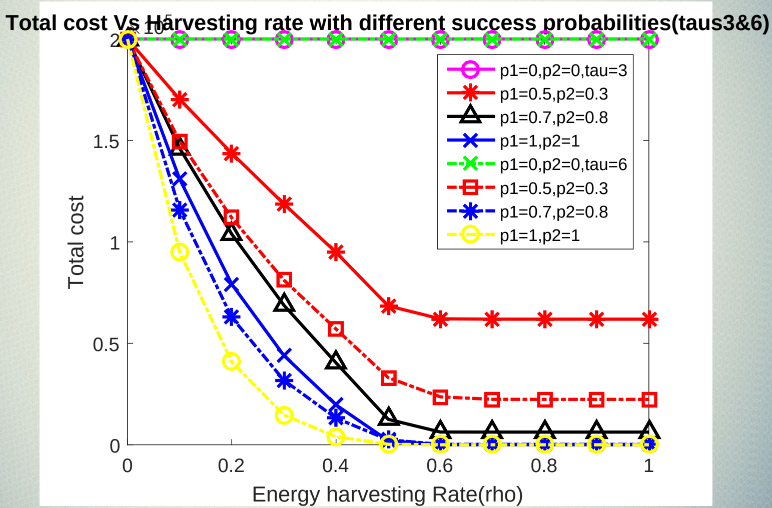
$$= \begin{cases} 10 & \text{if } b_n < E,\ u_n = 1 \textit{ and } x_n \geq \tau_n \\ 10 & \text{if } b_n < E,\ u_n = 1 \textit{ and } x_n < \tau_n \\ 1 & \text{if } b_n < E,\ u_n = 0 \textit{ and } x_n \geq \tau_n \\ 0 & \text{if } b_n < E,\ u_n = 0 \textit{ and } x_n < \tau_n \\ 1 & \text{if } b_n \geq E,\ u_n = 1 \textit{ and } x_n \geq \tau_n \\ 0 & \text{if } b_n \geq E,\ u_n = 1 \textit{ and } x_n < \tau_n \\ 2 & \text{if } b_n \geq E,\ u_n = 0 \textit{ and } x_n \geq \tau_n \\ 0 & \text{if } b_n \geq E,\ u_n = 0 \textit{ and } x_n < \tau_n \end{cases}$$

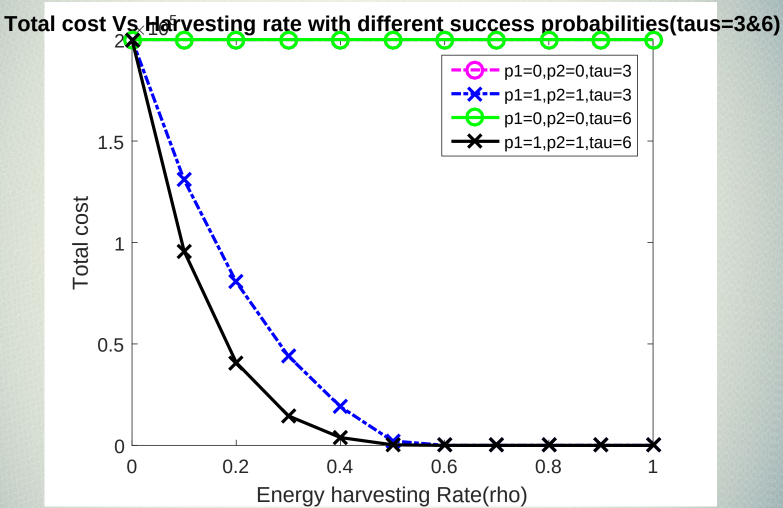
Heuristic policy

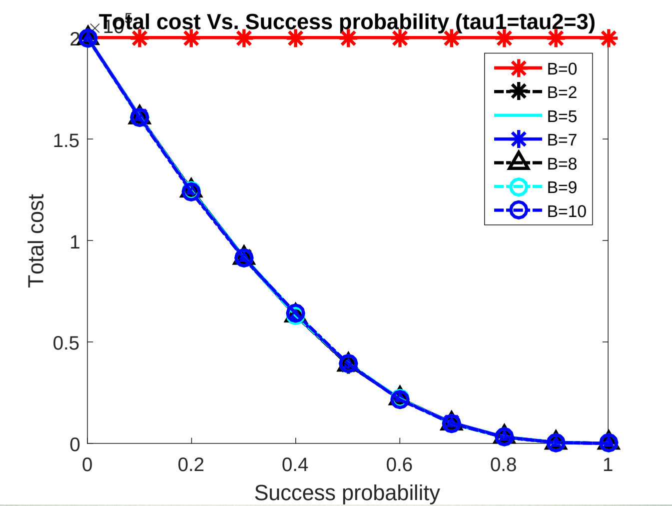
The Cost function used for Heuristic policy:
Cost Function:
The T-horizon optimal cost-to-go from initial state x is given by,

$$V_T(\mathrm{x}) := E\Big[\sum_{n=1}^{N}\Big(\sum_{i=1}^{M_T^{(n)}}(D_i^{(n)} - \tau_n)^+ + \Big(T - t_{D^{(n)}_{M_T^{(n)}}} - \tau_n\Big)^+\Big)\Big] \quad (2)$$

Heuristic policy Simulation Results:




Total cost Vs Harvesting rate with different success probabilities(taus=3&6)
$\times 10^5$
2
1.5
1
0.5
0
Total cost
0
0.2
0.4
0.6
0.8
1
Energy harvesting Rate(rho)
p1=0,p2=0,tau=3
p1=1,p2=1,tau=3
p1=0,p2=0,tau=6
p1=1,p2=1,tau=6


Total cost Vs. Success probability (tau1=tau2=3)
×10^5
2
1.5
1
0.5
0
Total cost
0
0.2
0.4
0.6
0.8
1
Success probability
B=0
B=2
B=5
B=7
B=8
B=9
B=10

Bibliography

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Thank You