# Energy Efficient Scheduling Policy:Problem Statement

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# Age-of-Information Aware Scheduling (P.Jhunjhunwala and S.Moharir)

- Age-of-information of a sensor in a time slot is defined as the number of time slots elapsed since the last measurement from the sensor was received by the monitoring station
- Channel is not probabilistic
- This paper gives a scheduling policy which minimizes the time average cost of the age of information
- This problem of minimizing cost is mapped to the problem of finding a minimum mean cost cycle in a weighted directed graph

# Algorithm

1. Create graph with finite number of vertices
2. Find minimum mean cost cycle $c$ using the algorithm given by Karp:

Let s be an arbitrary start vertex of graph G.For each vertex $v \in V$,let $F_n(v)$ be the minimum weight of an edge progression of length exactly $k$ from $s$ to $v$, of $\infty$ if no such edge progression exists

$$\lambda^* = \min_{v \in V} \underset{0 \leq k \leq n-1}{max} \left( \frac{F_n(v) - F_k(v)}{n - k} \right) \tag{1}$$

$\lambda^*$ gives the minimum cycle mean over all the directed cycles in G

# Optimal Energy-Efficient Regular Delivery of Packets in Cyber-physical Systems (X.Guo,R.Singh,P.R.Kumar,Z.Niu)

- Develops a scheduling policy which is energy efficient and simultaneously maintain regular deliveries of packets
- Channel is unreliable
- Formulates the problem as a Markov Decision Process (MDP) with a system cost consisting of the summation of the penalty for exceeding the inter-delivery threshold and a weighted transmission energy consumption
- An energy efficiency parameter $\eta$ is introduced to provide a balance between the two aspects

# Cont.

$$E\left[\sum_{n=1}^{N}\left(\sum_{i=1}^{M_T^{(n)}}(D_i^{(n)}-\tau_n)^+ + (T - t_{D_{M_T^{(n)}}^{(n)}} - \tau_n)^+ + \eta \hat{M}_T^{(n)} E_n\right)\right] \quad (2)$$

where

$N$,number of sensors

$M_T^{(n)}$,number of packets delivered for $n$-th client by time $T$

$D_i^{(n)}$,time between the deliveries of $i$-th and $(i+1)$-th packets for client $n$

$t_{D_i^{(n)}}$,time slot in which the $i$-th packet for client $n$ is delivered

$\hat{M}_T^{(n)}$,total number of slots in which $n$-th client is selected to transmit

# Cont.

Reduction to MDP problem

$$V_T(x) = \min_{\pi:\sum_n U_n \leq L} E\Bigg[\sum_{t=0}^{T-1}\sum_{n=1}^{N}\big(\eta E_n U_n(t)$$
$$+(X_n(t)+1-\tau_n)^{+}\mathbb{1}_{X_n(t+1)=0}\big)|X(0)=x\Bigg] \tag{3}$$

System state evolution

$$X_n(t+1) = \begin{cases} 0 & \text{if a packet of client is delivered in } t, \\ X_n(t)+1 & \text{otherwise} \end{cases} \tag{4}$$

where $X_n(t)$ is the time elapsed since the last delivery of client $n$'s packet

$$U_n(t) = \begin{cases} 1 & \text{,when sensor } n \text{ is selected to transmit} \\ 0 & \text{,else} \end{cases} \tag{5}$$

# Motivation

- In Age of Information paper, it provides an optimal solution for the scheduling problem to minimize the time average cost of the age of information by finding minimum mean cost cycle in the directed graph, here channel is reliable
- In the second paper, it provides the solution for scheduling problem which is energy efficient but considers only transmission energy
- Wireless energy harvesting sensors operate using energy harvested from environmental sources such as the sun, wind, vibrations, etc

# Motivation

- In sensors,energy is utilized in two operations,transmission and sensing of data
- Channel is unreliable,i.e.,each link will have different probability of successful transmission
- For the optimization problem defined below,solution will provide a policy which will conserve both operation's energy

# System Model

- Consider a system in which there are $N$ wireless sensors and one monitoring station (MS)
- Assume time is discrete,at most $m$ sensors can transmit simultaneously in a time slot
- In each time slot,a control message is broadcasted by MS to inform which set of $m$ sensors can transmit in current time slot
- Channel between MS and sensor $i$ is unreliable with probability of success as $p_i \in (0,1)$

# System Model

- Whenever a packet is not successfully transmitted or is not scheduled to transmit, it should incur a cost greater than before
- In a time slot,either transmission or sensing data for a sensor is possible
- $K$,total number of time slots

# System Model

1. State Space: The state space is a finite set

$$S = \{S_1, S_2, \ldots, S_N : S_i \in \{1, 2, \ldots, K\}\} \tag{6}$$

   $S$ represents the number of time slots elapsed since last successful transmission from $N$ sensors

2. State evolution equation

$$S_i(t+1) = \begin{cases} 0 & \text{if a packet of sensor } i \text{ is delivered in time } t \\ S_i(t) + 1 & \text{else} \end{cases} \tag{7}$$

3. Energy Space:

$$E = \{E_1, E_2, \ldots, E_N : E_i \in \{1, 2, \ldots, J\}\} \tag{8}$$

   $E$ represents the set of total energies associated with N sensors

4. Action Space:

$$U = \{U_1, U_2, \ldots, U_N : U_i \in \{0,1\}\} \tag{9}$$

$$U_i(t) = \begin{cases} 1 & \text{,when sensor } i \text{ is selected to transmit} \\ 0 & \text{,else} \end{cases} \tag{10}$$

$$Z = \{Z_1, Z_2, \ldots, Z_N : Z_i \in \{0,1\}\} \tag{11}$$

$$Z_i(t) = \begin{cases} 1 & \text{,when sensor } i \text{ senses a new data packet} \\ 0 & \text{,else} \end{cases} \tag{12}$$

# System Model

5. Observation Space:

$$V = \{V_1, V_2, \dots, V_N : V_i \in \{0, 1, 2, \dots, K\}\} \tag{13}$$

$$V_i(t) = \begin{cases} V_i(t-1) + 1 & \text{,if } U_i(t) = 0, Z_i(t) = 1 \\ V_i(t-1) - 1 & \text{,if } U_i(t) = 1, Z_i(t) = 0 \\ V_i(t-1) & \text{,if } U_i(t) = 0, Z_i(t) = 0 \end{cases} \tag{14}$$

6. State Transition probability

$$
\begin{aligned}
P_{x,y}(u,v) &= P[S(t+1) = y | S(t) = x, U(t) = u, Z(t) = z] \\
&= \prod_{i=1}^{N} P[S_i(t+1) = y_i | S_i(t) = x_i, U_i(t) = u_i, Z_i(t) = z_i] \\
\text{with } & P[S_i(t+1) = y_i | S_i(t) = x_i, U_i(t) = u_i, Z_i(t) = z_i] = \\
& \begin{cases} p_i & \text{if } y_i = 0, u_i = 1, z_i = 0 \\ 1 - p_i & \text{if } y_i = x_i + 1, u_i = 1, z_i = 0 \\ 1 & \text{if } y_i = x_i + 1, u_i = 0, z_i = 0 \text{ or } 1 \\ 0 & \text{else} \end{cases}
\end{aligned}
\tag{15}
$$

7. Immediate Cost function

$$C(S_i, U_i, Z_i) = \begin{cases} w_i S_i & \text{,if } U_i = 0 \\ 0 & \text{else} \end{cases} \quad (16)$$

where
$w_i$,weight associated with sensor $i$

# System Model

8. Objective function

$$\min_{\pi} E_{\pi} \sum_{t=1}^{K} \sum_{i=1}^{N} \left[ w_i S_i(t+1) + \eta (E_i^t U_i(t) + E_i^s Z_i(t)) \right] \tag{17}$$

subject to

$$\sum_{i=1}^{N} U_i(t) \leq m \tag{18}$$

$$\sum_{t=1}^{K} (E_i^t U_i(t) + E_i^s Z_i(t)) \leq E_i \tag{19}$$

$$V_i(t) > 0, \forall i, t \tag{20}$$

# Cont.

where
$p_i$,probability of successful transmission
$S_i(t+1)$,next state for sensor $i$
$\eta$,trade off factor
$E_i^t$,energy consumed by sensor $i$ for transmission of a packet
$E_i^s$,energy consumed by sensor $i$ for sensing a new packet

# Observation

- first part of the problem will incur a cost for not scheduling the sensor which will increase with each time slot
- while the second part of the equation deals with the energy used for transmission and sensing operations.
- Equation 20 helps to avoid the optimal solution of not sensing and not transmitting data at all
- One solution can be to sense data one time-slot before transmission but in that case,if there is an unsuccessful transmission then everytime there will be a new data queued for transmission,which will increase with number of unsuccessful transmission