System/Network Power Management in Underwater Sensor Networks

Energy-efficient and Lifetime-aware Routing Algorithm Using Markov Decision Process

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Overview

- Introduction
- Energy-efficient and lifetime-aware routing protocol
  - Stochastic model
  - Network solutions
- Future research plans

Research Direction

- Extend the network lifetime through energy-efficient networking protocols (e.g., routing, localization, etc.) and effective system power management

- Lifetime definitions:
  - When the first sensor node powers down
  - When a portion of the network nodes are dead
  - When the wireless network losses coverage for the first time
  - The mean expiration time
  - In terms of packet delivery rate
  - In terms of the number of alive flows

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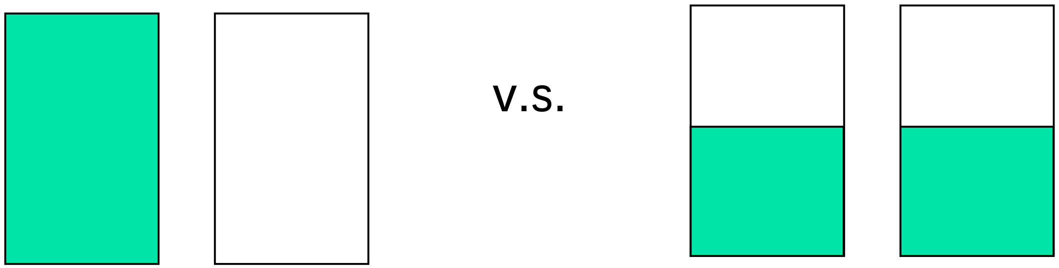
Energy-efficient and Lifetime-aware Routing

- Routing protocol
  - Energy-efficient: the minimum energy consumption for certain routing requests
  - Lifetime-aware: avoid unevenly energy distribution among sensor nodes



Related Work – Power Management

- Power management mechanisms directed by certain policy to save energy consumption in sensor nodes
- Related work
  - Dynamically managing various components in computer systems
    - Disk drive, CPU, memory, network card, display, etc.
    - Transition between different power states (e.g., DVFS)
  - Policy: when to transition to what low power state
    - Time-out
    - Greedy N-policy
    - Markov decision process based stochastic models
      - Discrete time approach by L. Benini, A. Bogliolo, G. Paleologo & G. Micheli
      - Continuous time approach by Qinru Qiu & Massoud Pedram
- Advantages of stochastic models
  - Using Markov decision process to find the optimum policy which minimizes the power consumption of a single computer system
  - The dynamic states of system can be effectively captured by the Markov chain model

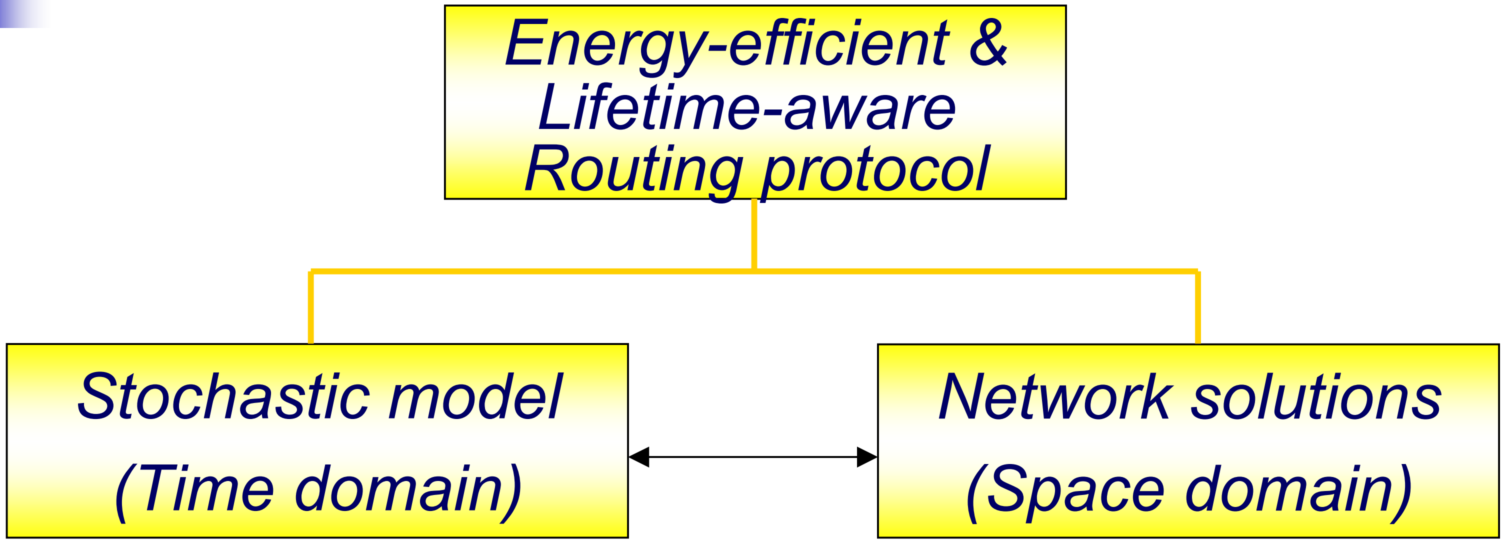
Related Work - General Routing Protocols

- Geographical routing by P. Xie & J. Cui
  - Using geographical information of sensors to choose forwarding nodes and save energy for the networks
  - Minimum number of hops from the candidate node to destination
  - Distance between the candidate and destination & some angle info
    - By reducing the number of hops from source to destination node, overall energy consumption will be reduced
- Maximizing network lifetime by J. Chang & L. Tassiulas
  - The residual energy is factored in when selecting forwarding nodes
  - Higher priority is given to nodes with higher power levels for forwarding
  - Advantages
    - The consideration of residual energy of each node will distribute the routing tasks more evenly in the network, thus network lifetime may be extended

Our Approach

- The power management technique is extended from a single node to the whole network in determining routing paths
- We apply the Markov decision process to find an optimal policy for data forwarding in underwater sensor networks (where and when to forward/drop)
  - The possible action of each node is simple
    - Two dynamic states: forward or drop
  - Parameters to represent the state of each node
    - Geographical position (d and Θ)
    - Residual energy (*Er*)
    - Recent forwarding history

Our Approach



Energy-efficient & Lifetime-aware Routing protocol

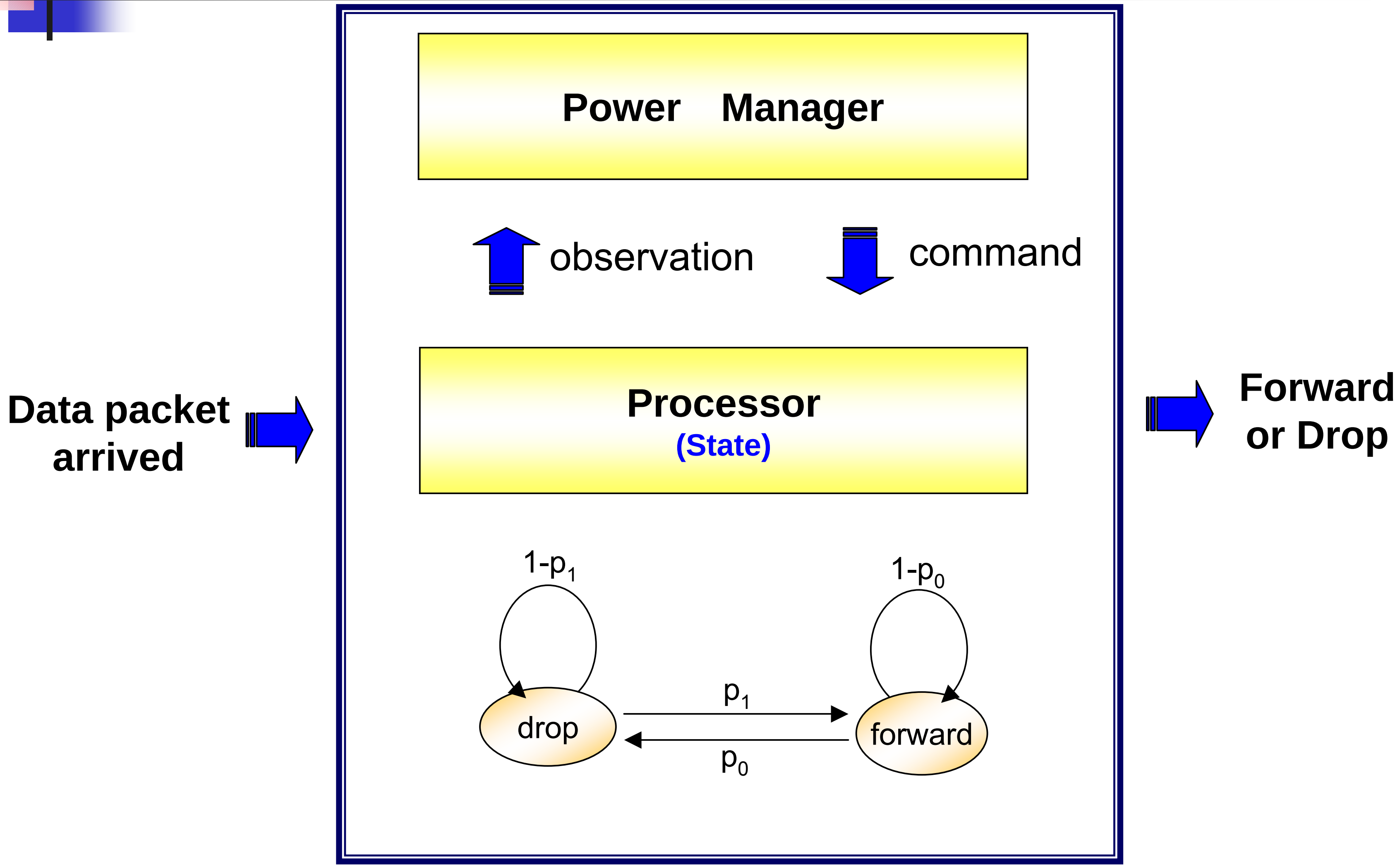
Stochastic model
(Time domain)

Network solutions
(Space domain)

- Markov process
  - Find optimum forwarding policy with minimum routing cost
- Routing parameters
  - Position info. (distance, angle)
  - Residual energy
  - Forwarding history

- Two-dimension
- Lifetime measurement
  - Variance of residual energy in nodes

System Model



Data packet arrived

Power Manager

observation

command

Processor

(State)

$1-p_1$

$1-p_0$

drop

p_1

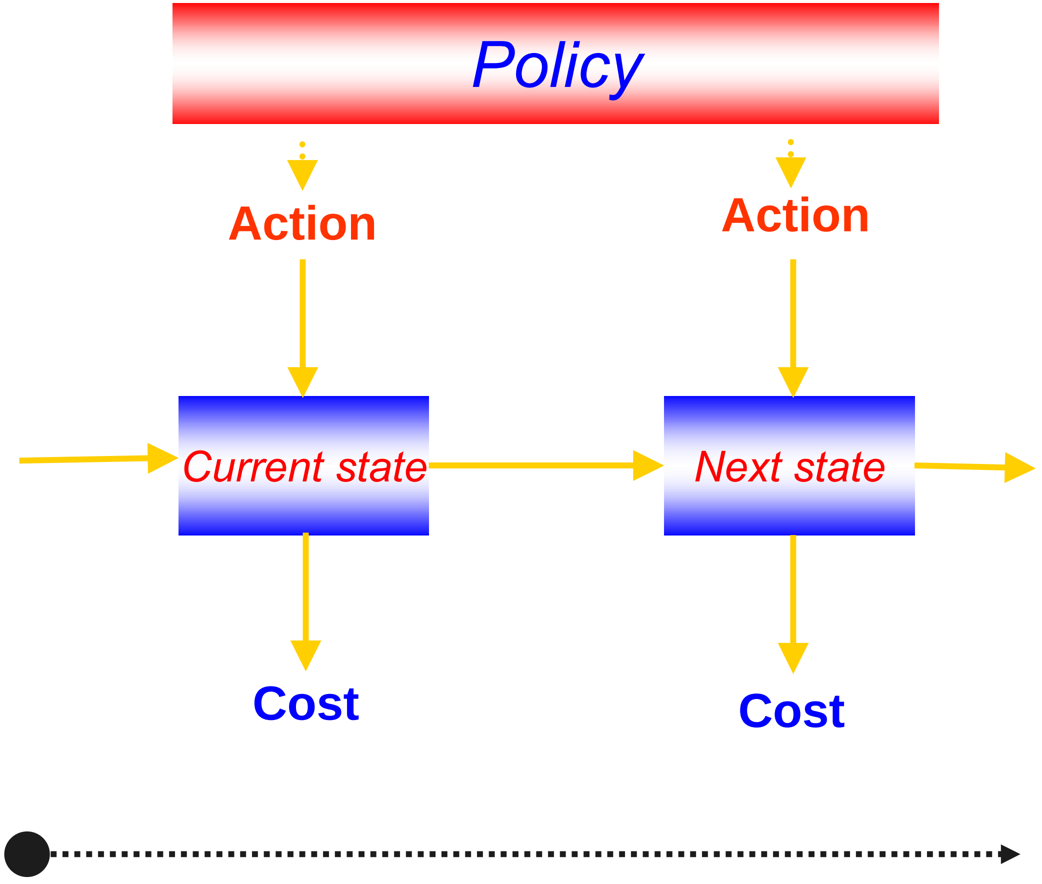
p_0

forward

Forward or Drop

Stochastic Model

- Markov decision process



Policy

Action

Action

Current state

Next state

Cost

Cost

Discounted factor (inflation, error , etc.)

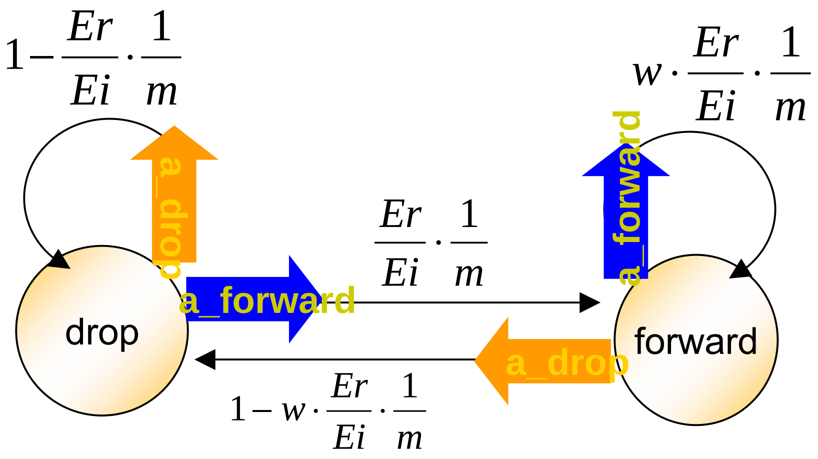
For discrete states i=1,2,…N

- A policy set $\pi = \{\pi_i\}$
- An action set $A = \{a_i\}$
- A state set $S = \{s_i\}$
- A cost set $C = \{c_i\}$
- Discount factor=β, $0<\beta<1$

"How to find the policy that can minimize the cost?"

Our Stochastic Model

- A Markov decision process model



- *A state set S = {drop, forward}*
- *A cost set C = {log(m)/m (or m/exp(m), 1}*
- *An action set A = {a_drop, a_forward}*
- *A discount factor β → 0<β<1*

- A transition probability fuction

P_{ij}^{a} = probability(next=j|current=i, action a)

$$\begin{array}{cc} & \begin{array}{cc} \textit{p\_drop} & \textit{p\_forward} \end{array} \\ \begin{array}{c} \textit{drop} \\ \textit{forward} \end{array} & \begin{pmatrix} 1-\frac{Er}{Ei}\cdot\frac{1}{m} & \frac{Er}{Ei}\cdot\frac{1}{m} \\ 1-w\cdot\frac{Er}{Ei}\cdot\frac{1}{m} & w\cdot\frac{Er}{Ei}\cdot\frac{1}{m} \end{pmatrix} \end{array}$$

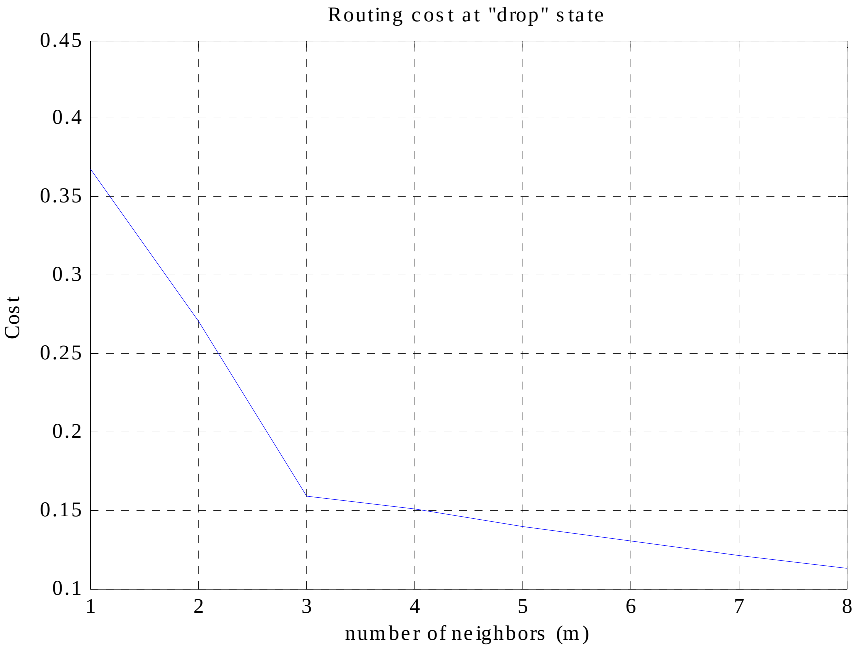
where Er: residual energy
Ei: initial energy
m: # of neighbors
w: weight, 0<w<1

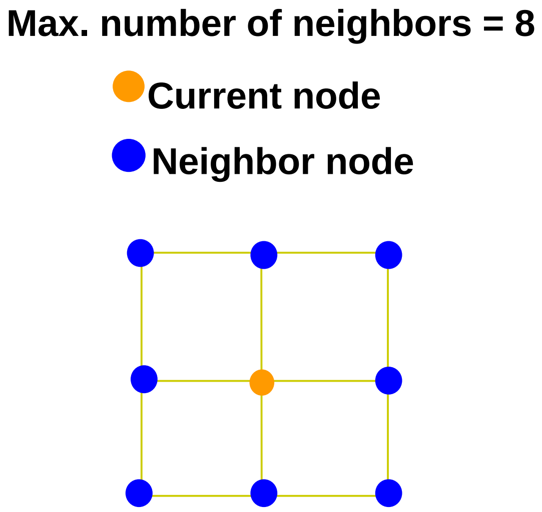
- *A policy set π = {π1, π2, π3, π4}*

	state	action		state	action
π 1	drop	a_drop	π 2	drop	a_drop
	forward	a_drop		forward	a_forward
	state	action		state	action
π 3	drop	a_forward	π 4	drop	a_forward
	forward	a_drop		forward	a_forward

Parameter Selection

- Routing cost (power & connectivity)
  - Connectivity cost $CC = \begin{cases} \log(m)/m, & \text{state = drop \& } m \geq 3; \\ m/\exp(m), & \text{state = drop \& } 0<m<3; \\ 0\ , & \text{otherwise} \end{cases}$
  - One hop power consumption $CP = \begin{cases} 1, & \text{state = forward;} \\ 0, & \text{otherwise} \end{cases}$
  - Total cost $C = CC + CP$





Max. number of neighbors = 8

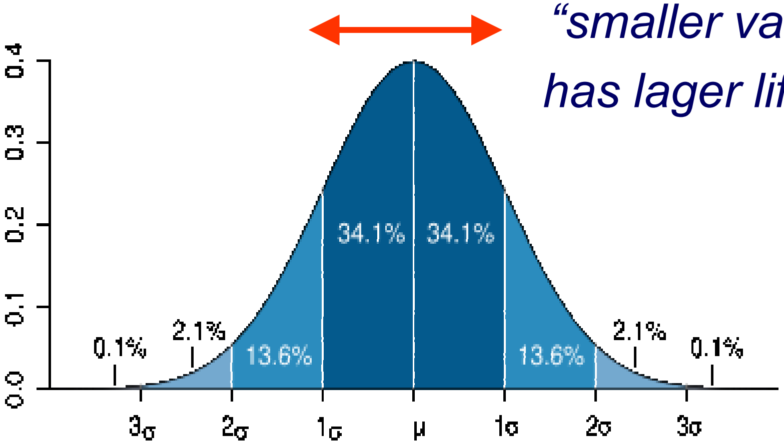
● **Current node**

● **Neighbor node**

Network Solutions

- From time-domain to space-domain
  - Multi-dimensional Markov process (?)

- Lifetime measurement
  - Variance of residual energy in nodes, or can be simplified as the entropy measure



"smaller variance has lager lifetime"

$$Entropy = \sum_{j=1}^{n} \left|\log(Er_j / Ei_j)\right|$$

Discussions

For MDP-based routing algorithm:

- How to decide parameters in the MDP model?
- Which algorithm may be effective for network solution?
  - How to incorporate position information, residual energy, etc. in the cost function?

Future Work

- Apply stochastic models to other networking algorithms, e.g., MAC, localization, etc., for energy saving and lifetime extension
- Refine the lifetime definition
- Lifetime estimation model and simulation

Appendix

Markov Process

- Definition: the future value is independent of the past values given the present value:

For $t_1 < t_2 < \ldots < t_n$

$$P[\underbrace{x(t_n)}_{\text{future}} \leq x_n | \underbrace{x(t_{n-1})}_{\text{present}}, \underbrace{x(t_{n-2}), \ldots , x(t_1)}_{\text{past}}\} = P\{\underbrace{x(t_n) \leq x_n | x(t_{n-1})}_{\text{“depend only on present value”}}$$

- Class of Markov processes

t x(t)	Continuous	Discrete
Continuous	Markov process	Markov Sequence
Discrete	Continuous time Markov Chain	Markov Chain