Carnegie Mellon University

Intelligent Communication Planning for Constrained Environmental IoT Sensing with Reinforcement Learning

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Overview

- **Constrained IoT Environmental Sensing**
  - Motivation & Challenges
- **Problem Formulation**
  - System Model
  - Data Value
- **EnvSen Framework**
- **Evaluation**
- **Conclusion**

IoT Sensing

- IoT technologies have enabled building numerous ***data-driven*** applications/services
- *Interconnecting* a vary large number of devices equipped with ***networking***, ***sensing***, and ***processing*** capacities

- Ubiquitous sensing capabilities
- Healthcare, civil engineering, environmental monitoring

Motivating Example: Wildfire Tracking

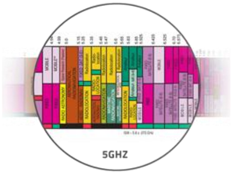
Large wildfires cause severe air pollution, burn *millions* of acres…

To fight wildfires and reduce damage:

- Fire chiefs rely on ***real-time*** environmental data to track and predict wildfire spread
- IoT devices: collaboratively collecting wildfire-relevant data in real time (wind direction/speed, temperature, etc.)

Challenge 1: Resource Constraints

- **Constrained Communication:**
  - LoRa, Sigfox…
  - Stringent bandwidth constraints



Wireless spectrum

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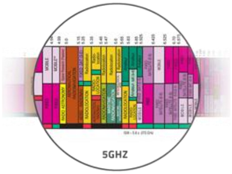
  - Maintain up to 10 years of battery life



Wireless spectrum

Batteries

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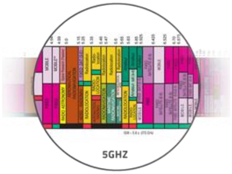
  - Will quickly *drain IoT sensors' limited power supply* in order to turn on a radio and use it for data transmission



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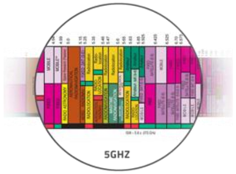


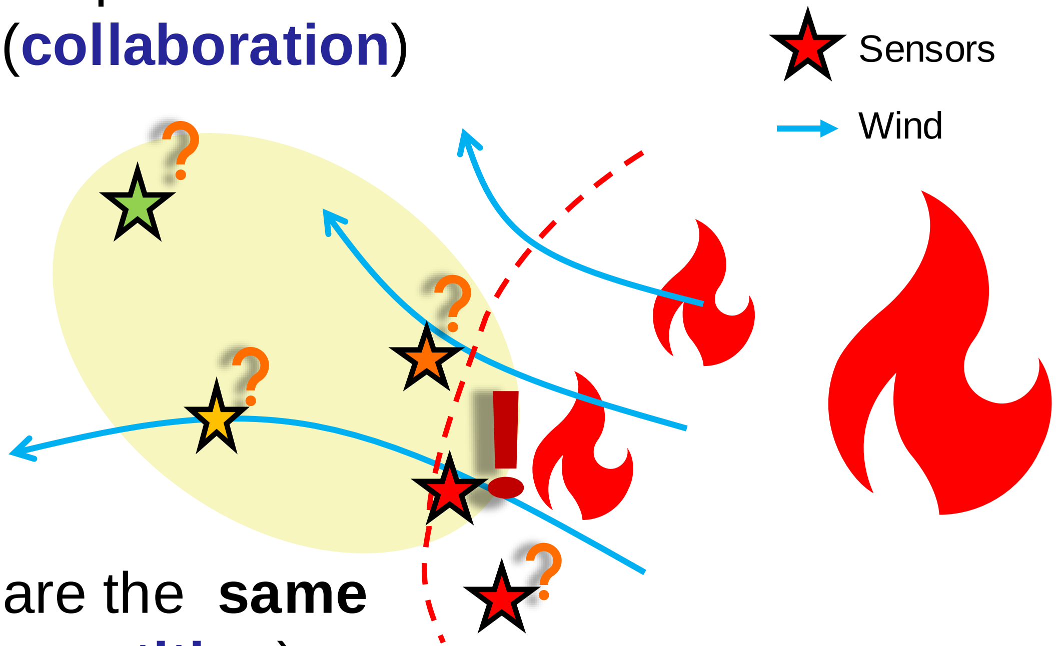
Wireless spectrum

Batteries

Problem: How to **efficiently** manage data communication and collect data from **numerous** IoT devices?

Challenge 2: Spatiotemporal Correlation

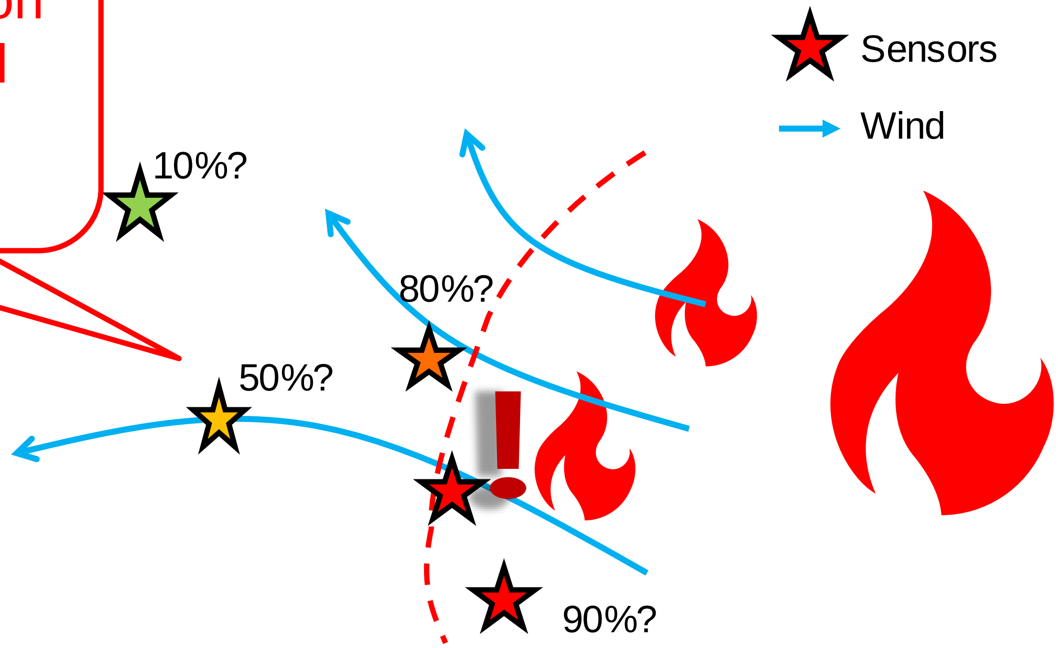
Adjacent nodes sample
correlated data (**collaboration**)



Adjacent nodes share the **same resource pool** (**competition**)

Challenge 3: Define Data Value

How the local observation contribute to the global sensing problem?



Communication Planning

Optimize data sampling & transmission of IoT devices

Objective: maximize the quality of collected data
s.t. resource constraints.

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Optimize data sampling & transmission of IoT devices

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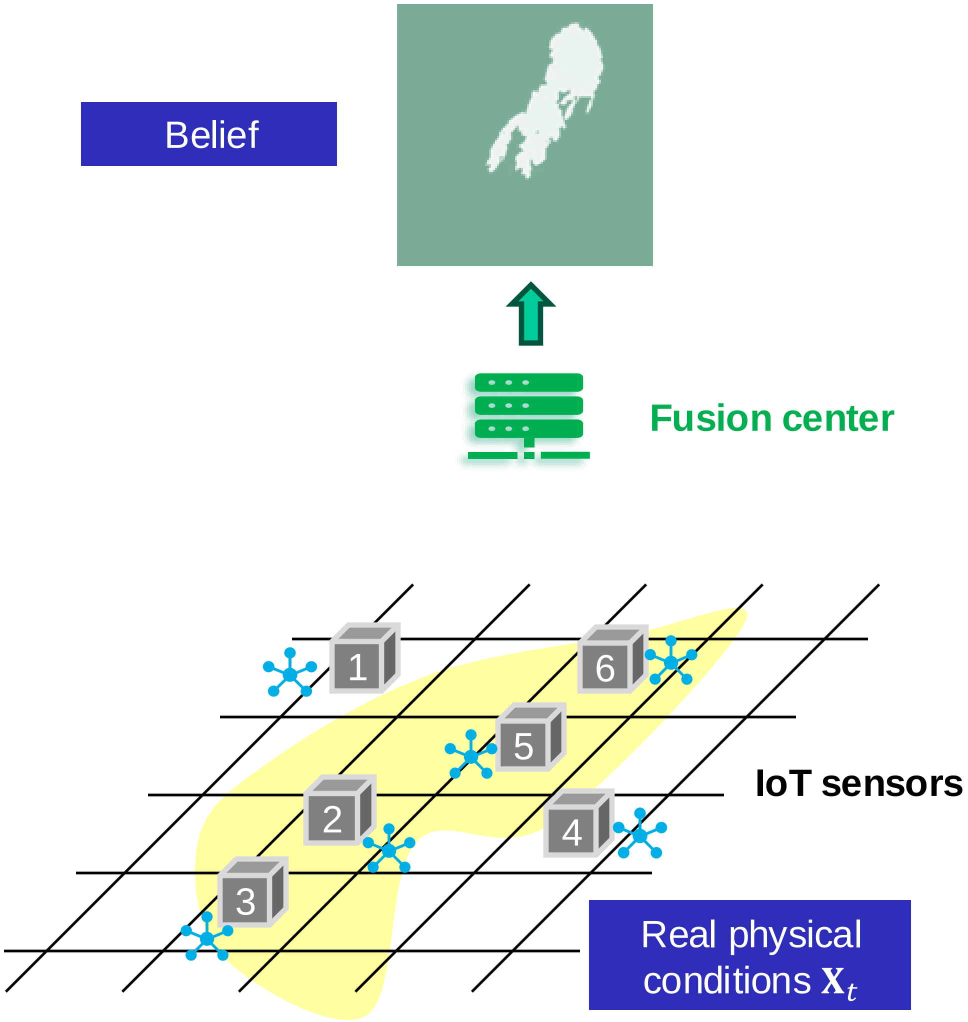
- ***Requirement to coordinate data collection and transmission***
  - Sensor data can be **correlated in space and time**
  - Collect useful (not redundant) data while respecting the resource constraints
- ***Highly decentralized***
  - Due to limited wireless spectrum/power supply
  - **No direct point-to-point communication**
  - **Limited information sharing** across the network

Problem Formulation

- System Model
- Data Value

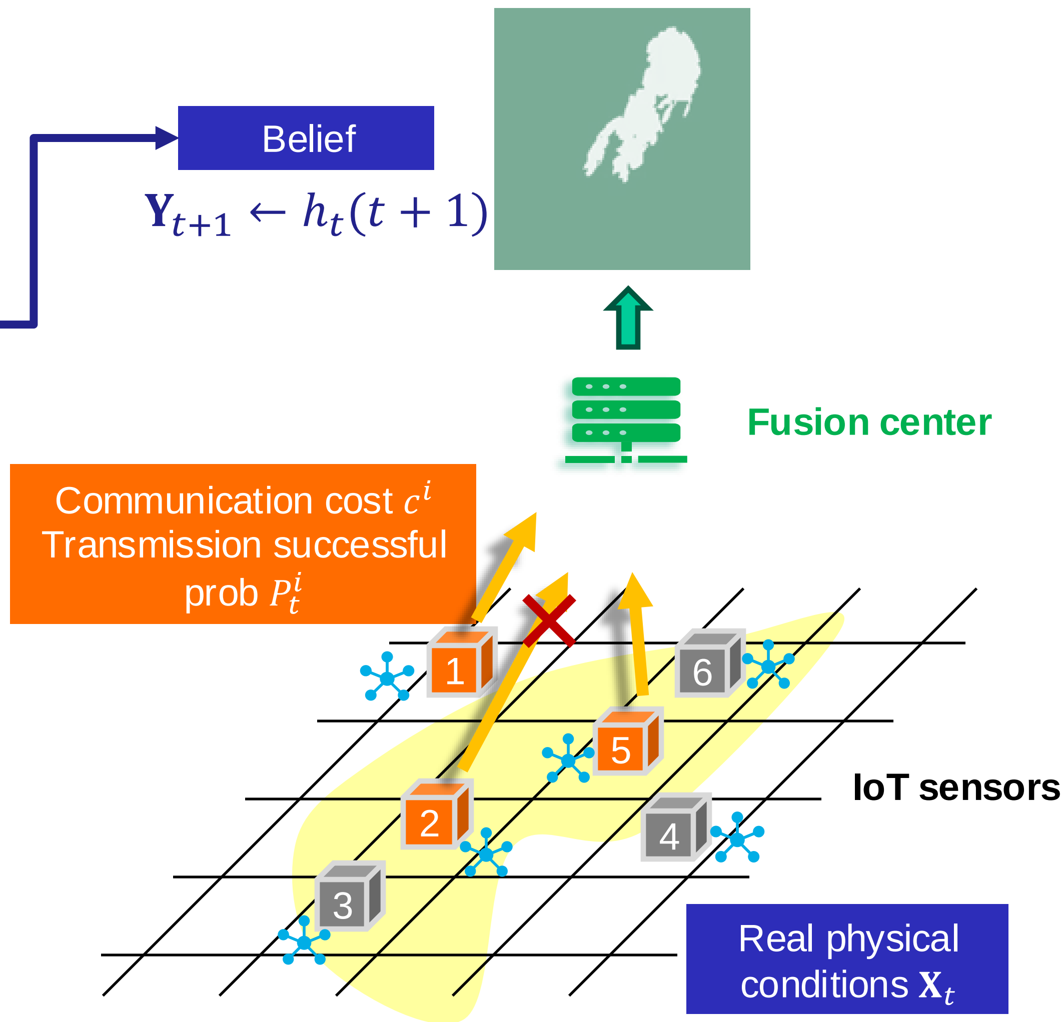
System Model



System Model

Fusion center

Time	Acquired data	
⋮	⋮	h_{t-1}
t	x_t^1, x_t^5	h_t



System Model

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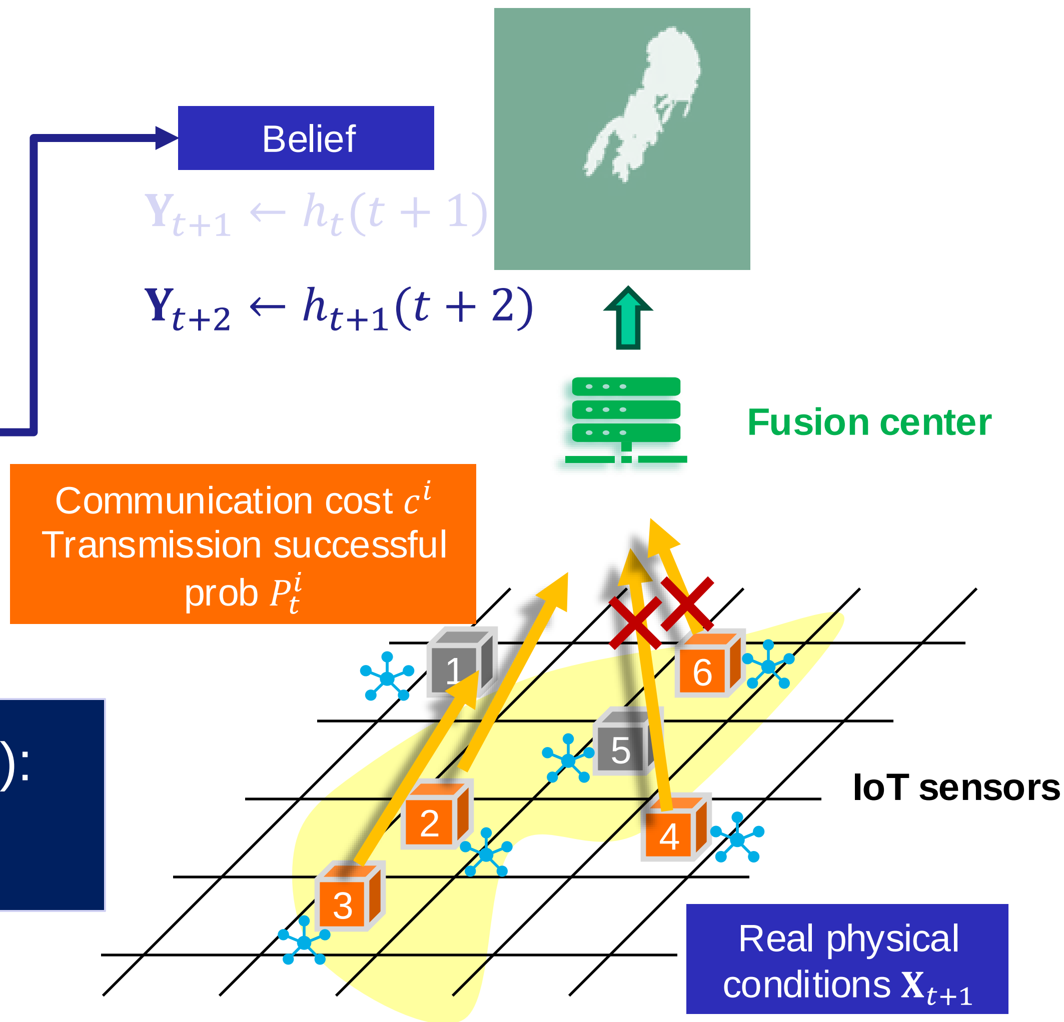
Time	Acquired data	
⋮	⋮	h_{t-1}
t	x_t^1, x_t^5	h_t
$t+1$	x_{t+1}^2, x_{t+1}^3	h_{t+1}
⋮	⋮	

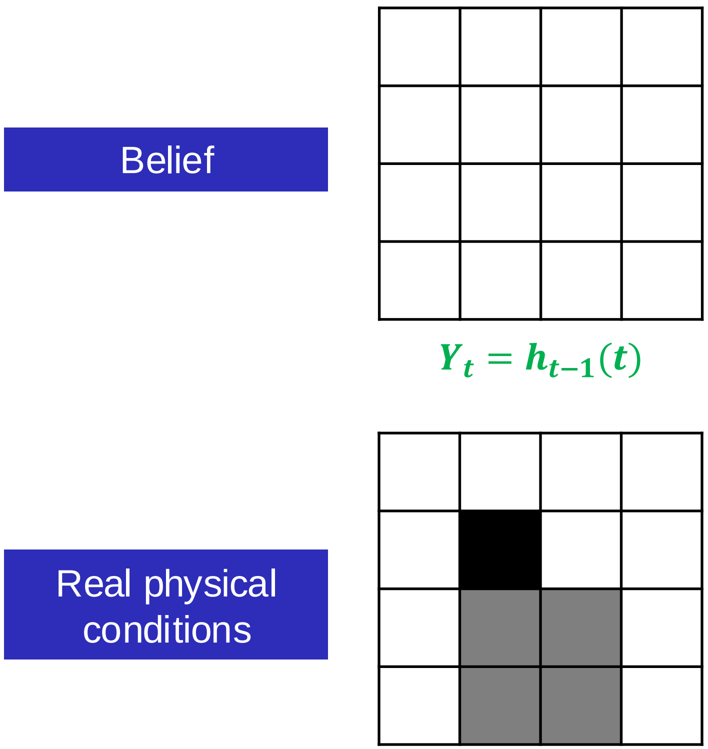


Error loss (application specific):

$$L_t = l(\boldsymbol{X}_t - \boldsymbol{Y}_t)$$

Data Value

Goal: minimize the error loss over time



$Y_t = h_{t-1}(t)$

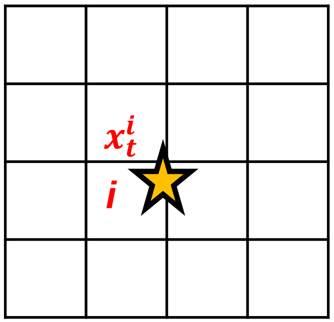
X_t

Error loss (before): $L_t = l(X_t - Y_t)$

Data Value

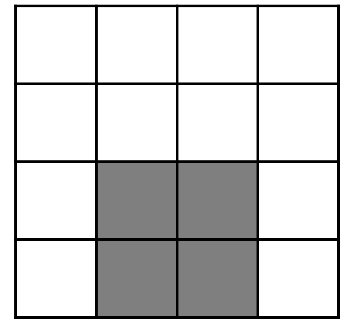
Goal: track the environmental conditions as ***accurately*** as possible over time

Belief



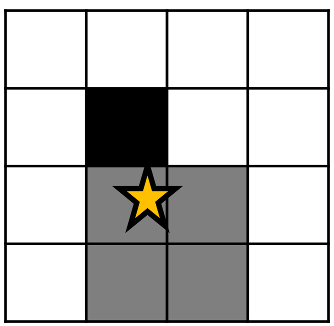
$Y_t = h_{t-1}(t)$

If x_t^i is collected at time t



$h_t^{+i}(t)$

Real physical conditions



X_t

New error loss:

$L_t^i = l\left(X_t - h_t^{+i}(t)\right)$

Data value of x_t^i :

$v_t^i = L_t - L_t^i$

Error loss (before): $L_t = l(X_t - Y_t)$

Communication Planning

Collectively maximize the sum over the value of the collected data at the expense of the communication cost.

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- **Communication cost**

$$c_t = \sum_{i \in I_t} c^i$$

I_t: the set of sensors that transmit at t

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- **Expected data value**

$$v_t = \sum_{i \in I_t} P_i(I_t) v_t^i$$

$P_i(I_t)$: the transmission successful probability of device *i* if the set I_t are transmitting at *t*

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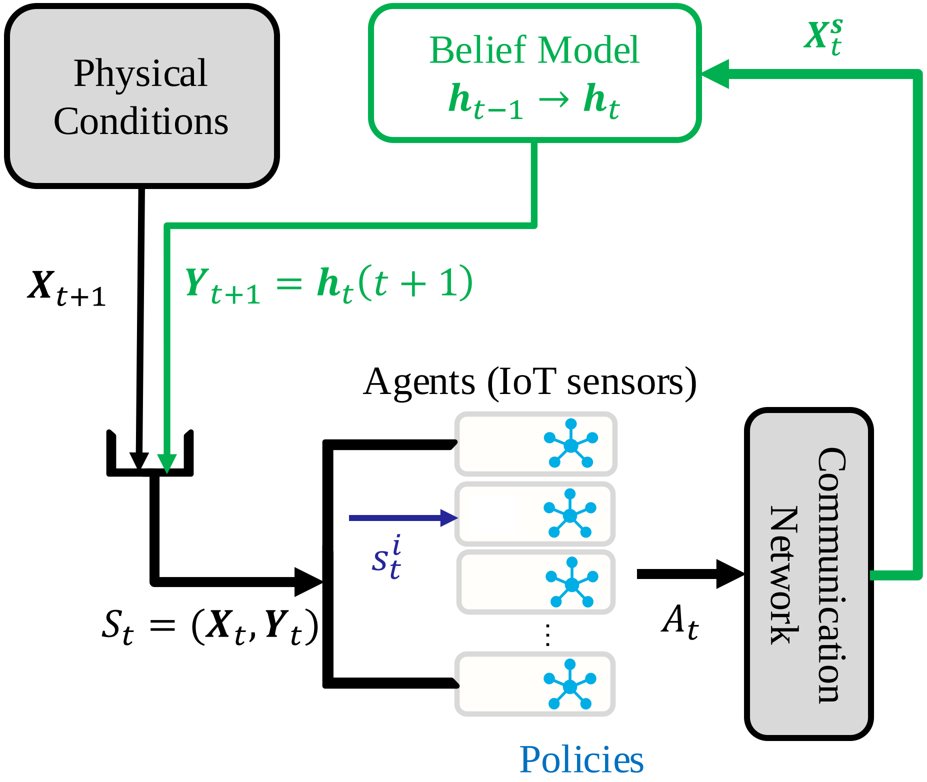
- **System objective**

$$\max_{\pi} \mathbb{E}_{I_t \sim \pi} \left[\sum_{i \in I_t} P_i(I_t) v_t^i - w c^i \right]$$

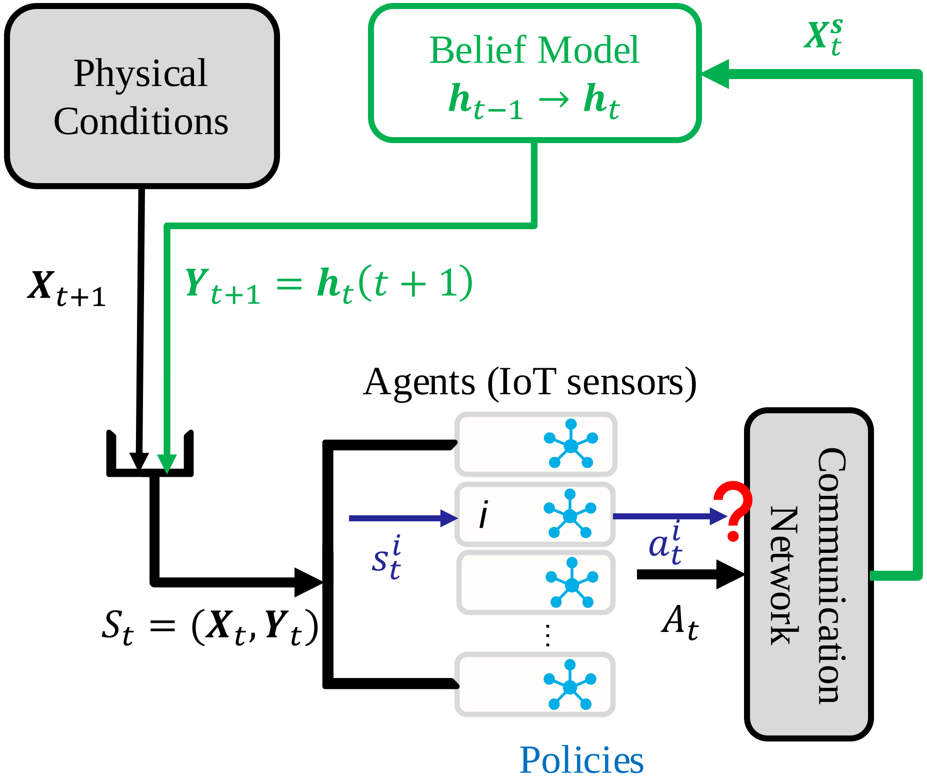
EnvSen: RL Framework

EnvSen Framework



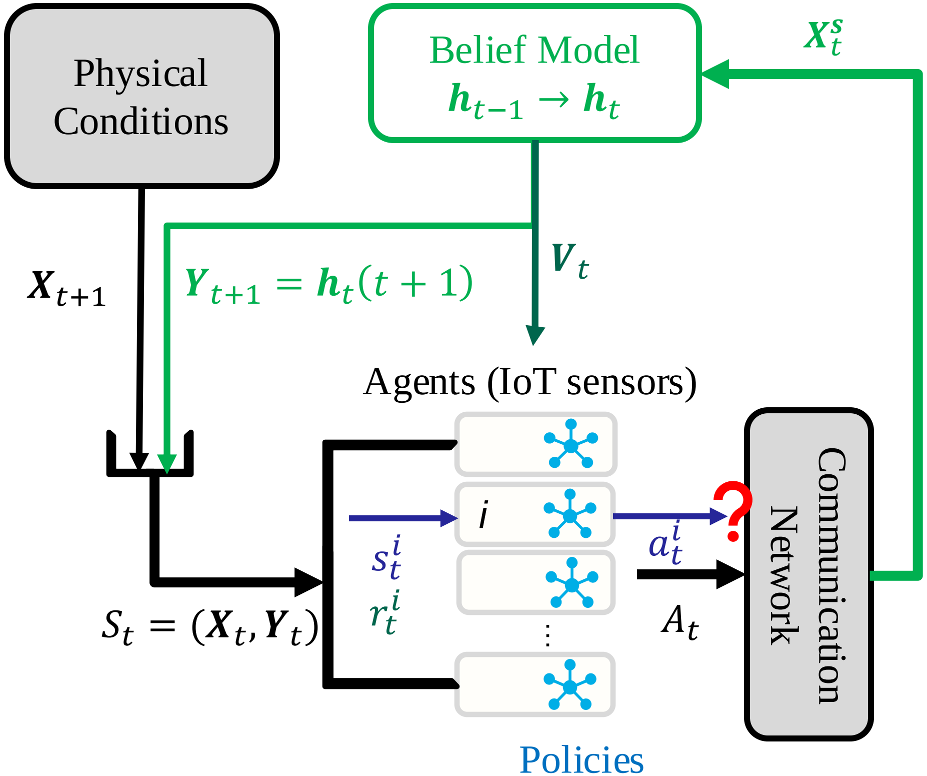
- **State:** local obs + belief
  $s_t^i = (x_t^i, Y_t)$

EnvSen Framework



- **State:** local obs + belief
  $s_t^i = (x_t^i, \boldsymbol{Y}_t)$
- **Action:** send or not
  $a_t^i \in \{1,0\}$

EnvSen Framework (training)



- **State:** local obs + belief
  $s_t^i = (x_t^i, \boldsymbol{Y}_t)$
- **Action:** send or not
  $a_t^i \in \{1,0\}$
- **Reward:**
  $r_t^i = a_t^i(\mathbf{1}_{succ} v_t^i - wc^i)$

EnvSen vs. Prior Work

- **vs. IoT sensing:**
  - Uniquely considers distributed communication coordination of multiple nodes
  - No device-to-device communication
- **vs. mobile crowdsourcing:**
  - In fixed locations in an ad hoc manner
- **vs. Mult-Agent RL on communication coordination:**
  - No centralized orchestration
  - Realistic communication constraints
  - Dedicated sensing objective

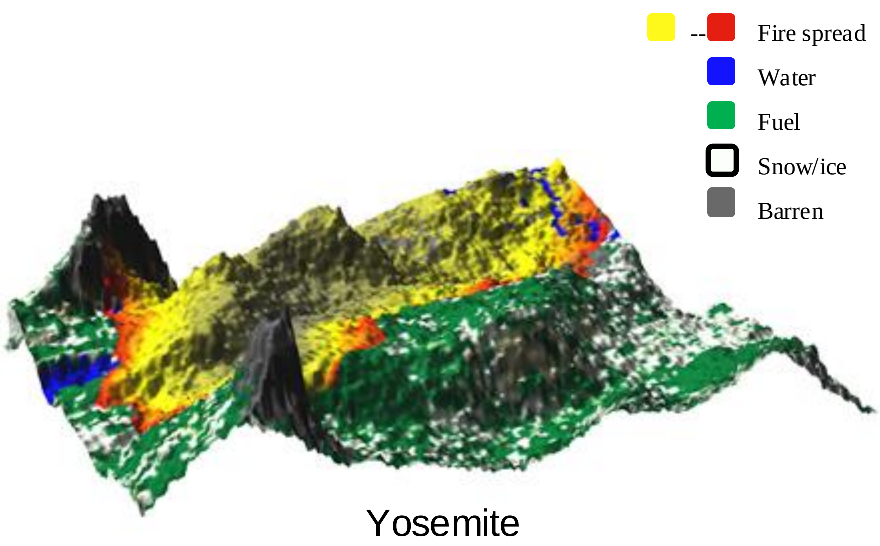
Evaluation

- Experiment Setup
- Performance
- Tradeoff

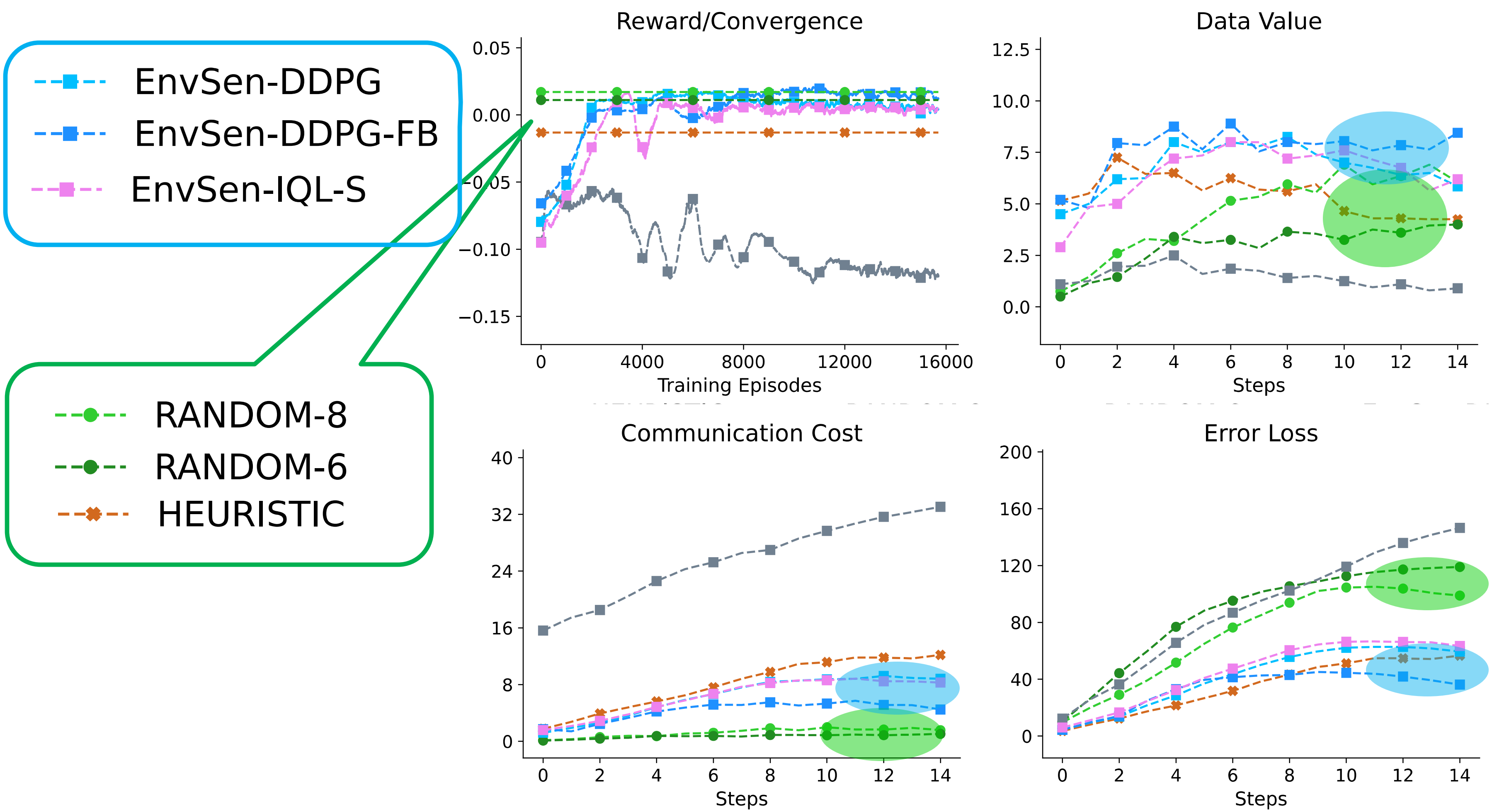
Setup

Wildfire tracking & 200 sensors.

- **Wildfire data:**
  - GRASS GIS
  - 200 instances of realistic propagation
- **LoRa communication network**
  - Log-distance path loss
  - 4 channels, one gateway

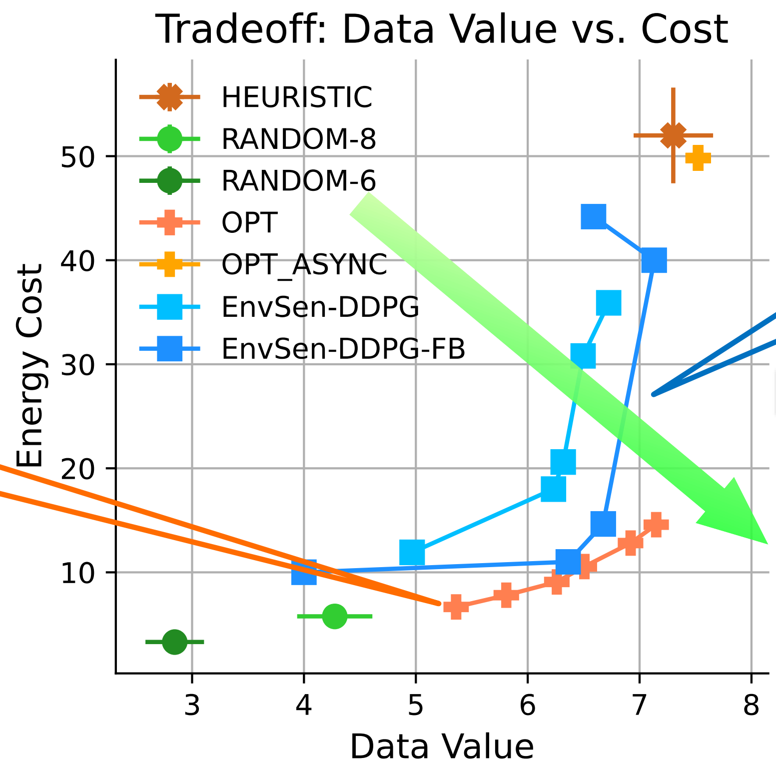


Performance



Tradeoff (varying *w*)

(Bandwidth-limited channel)



OPT: centralized optimal policy with full information

EnvSen: adapt to varying weighting factor and very close to the optimal policy

Better

Able to balance the tradeoff between conserving device power and maintaining high tracking accuracy.

Conclusion

- **Formulate the constrained IoT sensing problem**
  - Combine the energy cost of communication, tracking accuracy, and models for successful data transmission
- **Propose EnvSen (MARL solution)**
  - Define data value based on the dedicated sensing objective
- **Evaluate on realistic wildfire propagation data**
  - Balance the tradeoff between conserving device power and maintaining high tracking accuracy

Thanks!

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