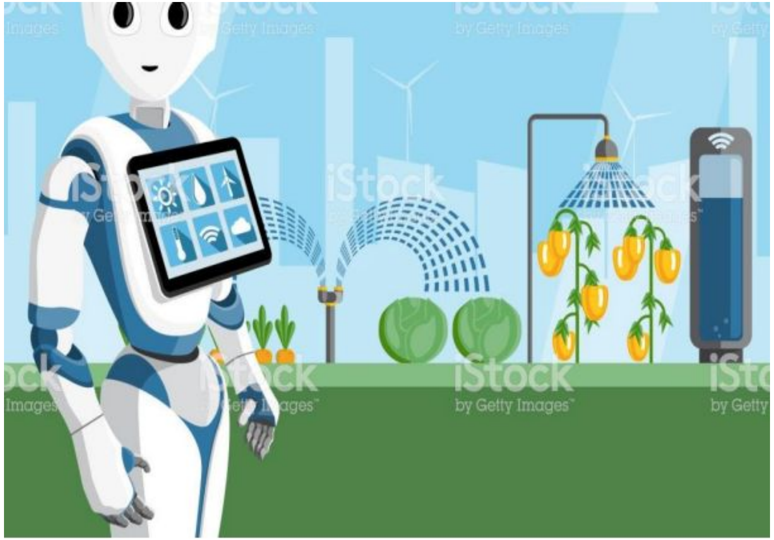
WISDOM: Watering Intelligently at Scale with Distributed Optimization and Modeling

Daniel A. Winkler
University of California, Merced
dwinkler2@andes.ucmerced.edu

Alberto E. Cerpa
University of California, Merced
acerpa@andes.ucmerced.edu



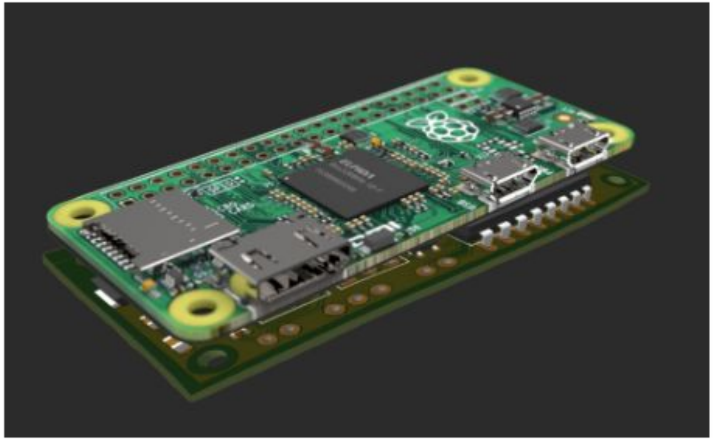
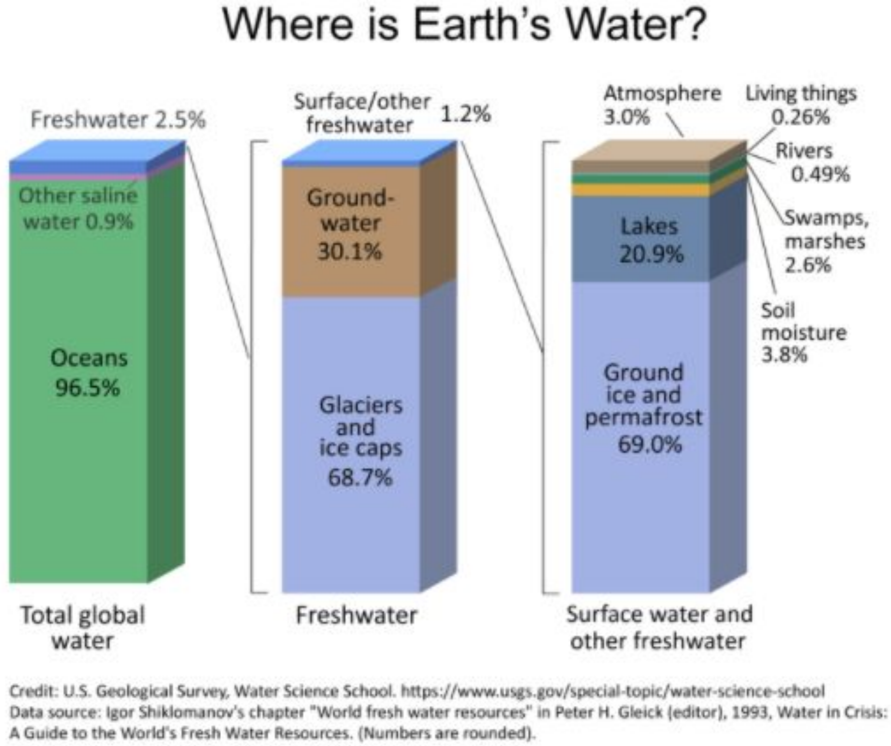


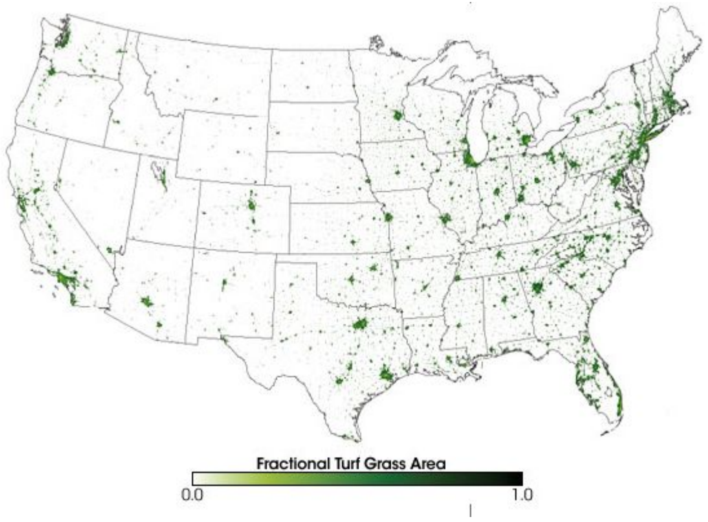
Figure 6.3: Prototype WISDOM device

Outline

- Background and Motivation
  - Centralized Control
  - Distributed Control
- WISDOM System
  - Modeling
  - Hardware
- Experiments and Results
  - WISDOM vs. ET
  - WISDOM vs. PICS
- Conclusions

Fresh Water is Not Abundant





In continental U.S. alone:

- 128,000 square kilometers
  - Estimated 3x more than corn
- 9 billion gallons/day to irrigate
  - Landscaping 30% - 70% of residential water use

Systems aren’t great

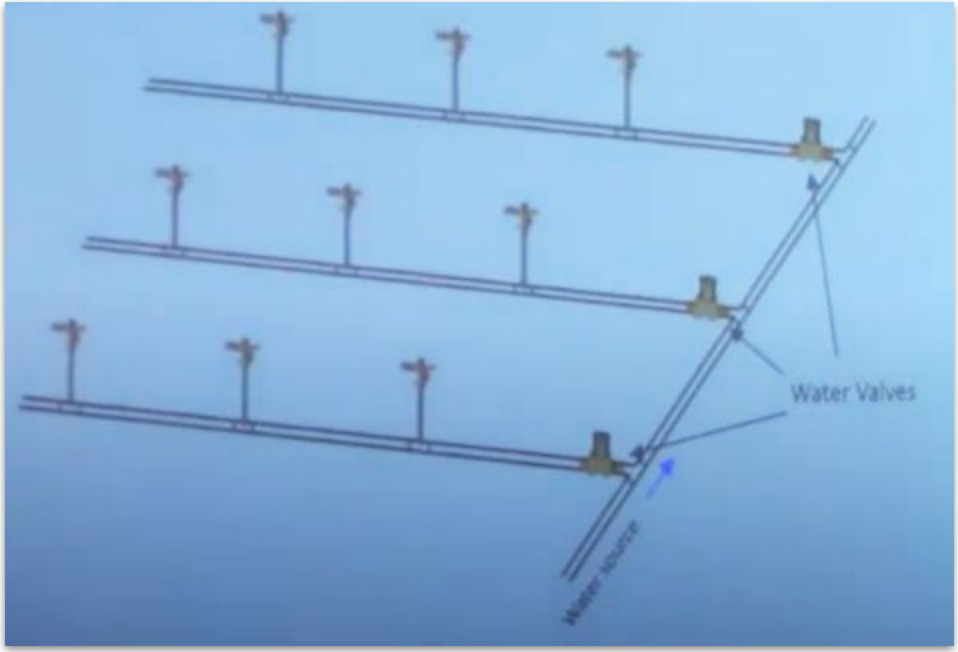
It’s easy to find irrigation systems that are not doing their jobs properly …

Primary offenses:

- Under-watering
  - Bad quality
- Over-watering
  - Bad efficiency
  - Erode soil
  - Leeches fertilizer chemicals

Irrigation System Architecture

Depending on the size of the system, the values may be placed on each run, like this:



No hierarchical control

Irrigation System Architecture

Water needs are not necessarily constant everywhere

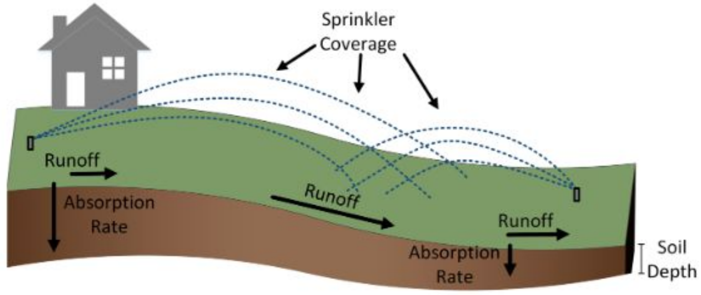
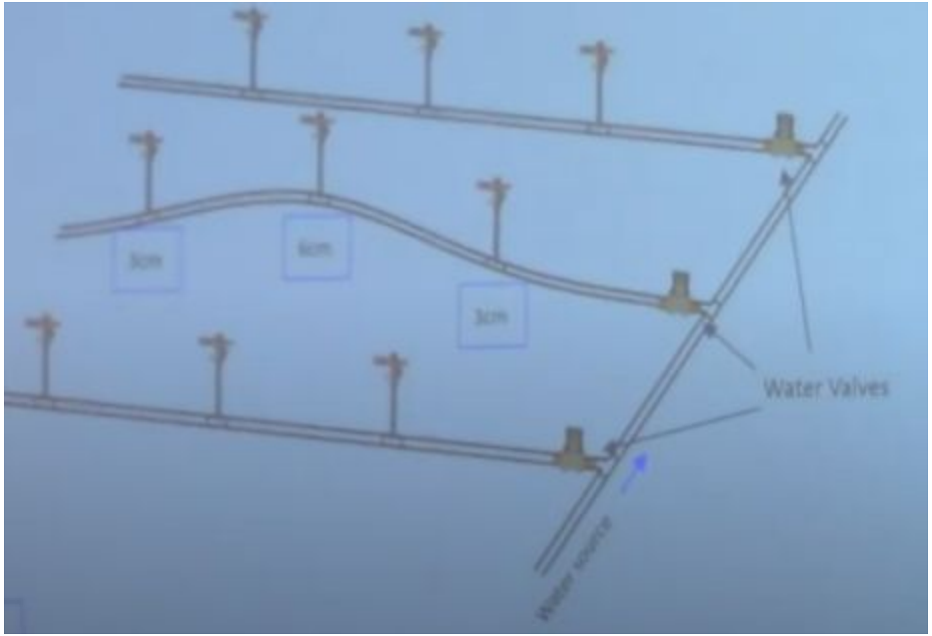
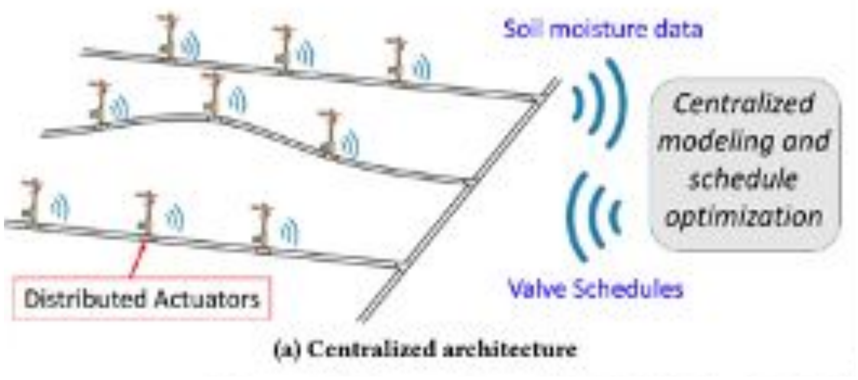


Figure 5.10: Sources of water movement *during* irrigation (Short-term)



Different plants, soil type, soil depth, slop, shadowing, … .etc

Distributed Actuation and Centralized Control



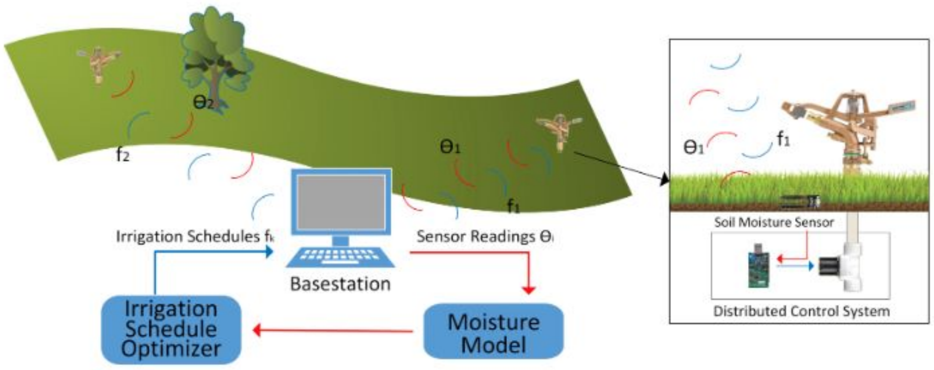
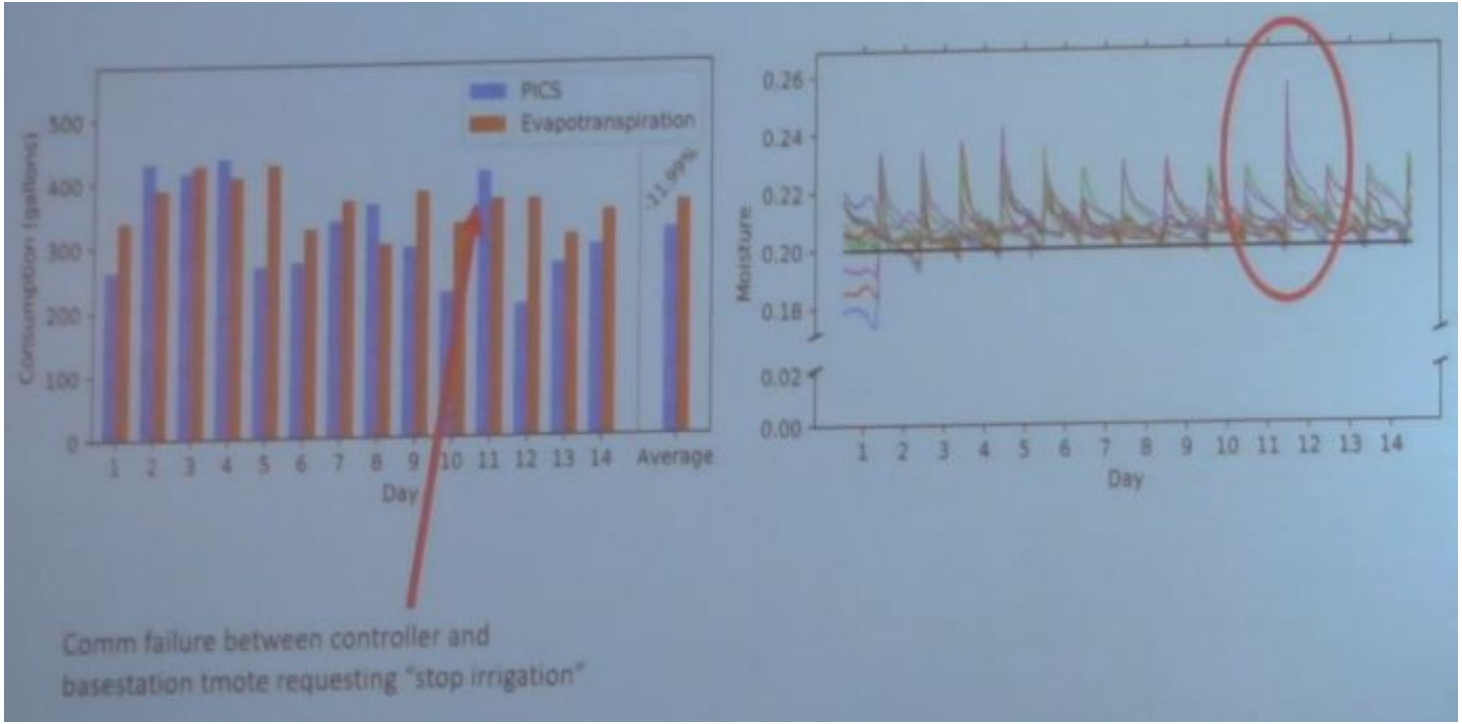


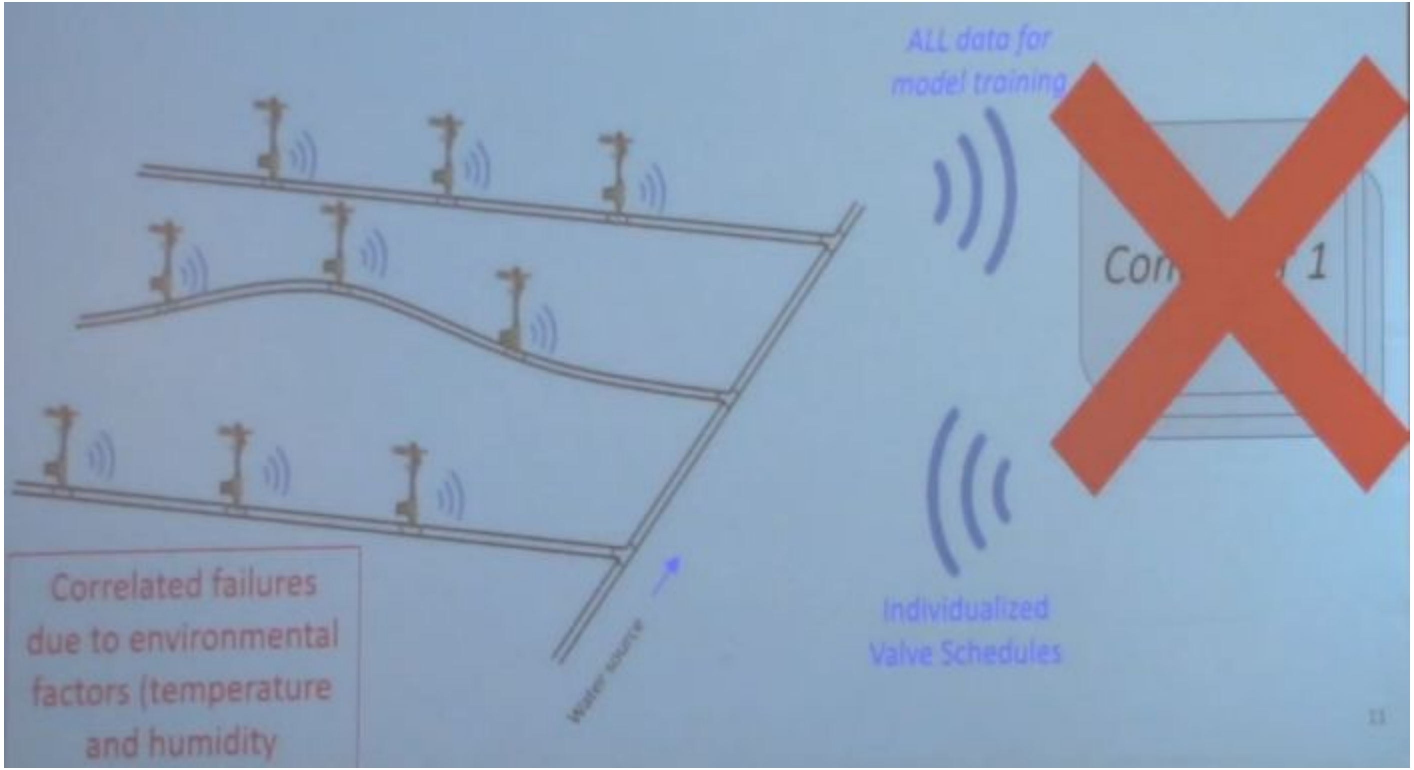
Figure 4.1: DICTUM System Architecture

Each sprinkler head has a node with a solenoid for on/off control and a moisture sensor

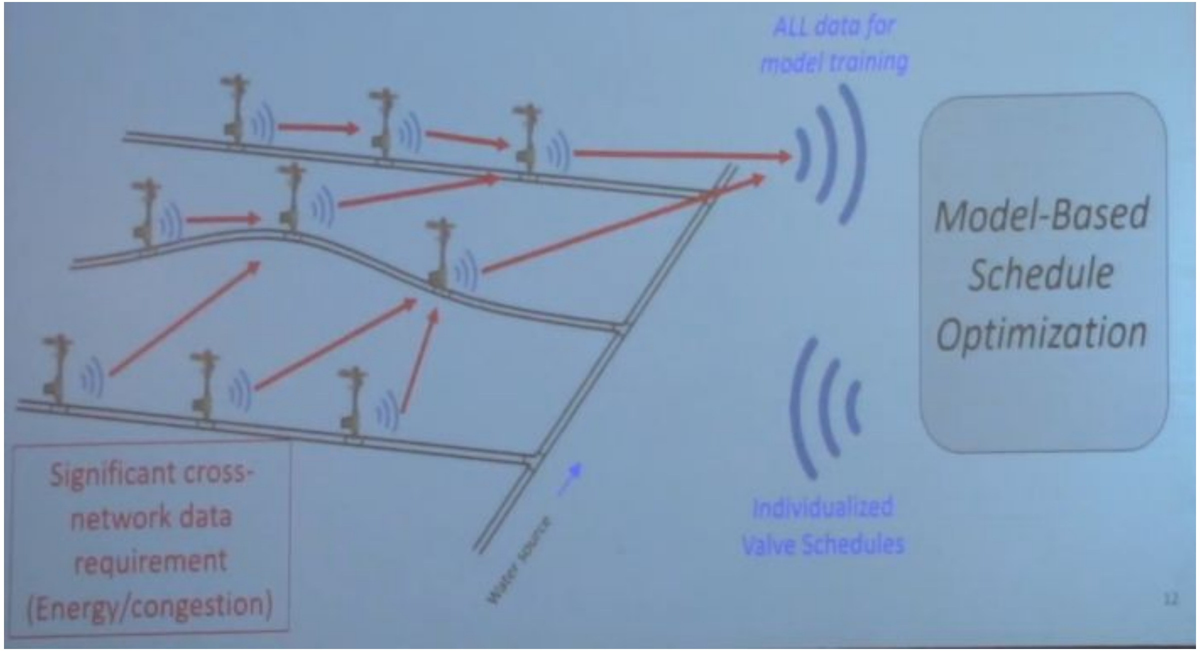
Centralized Control - Single Point of Failure



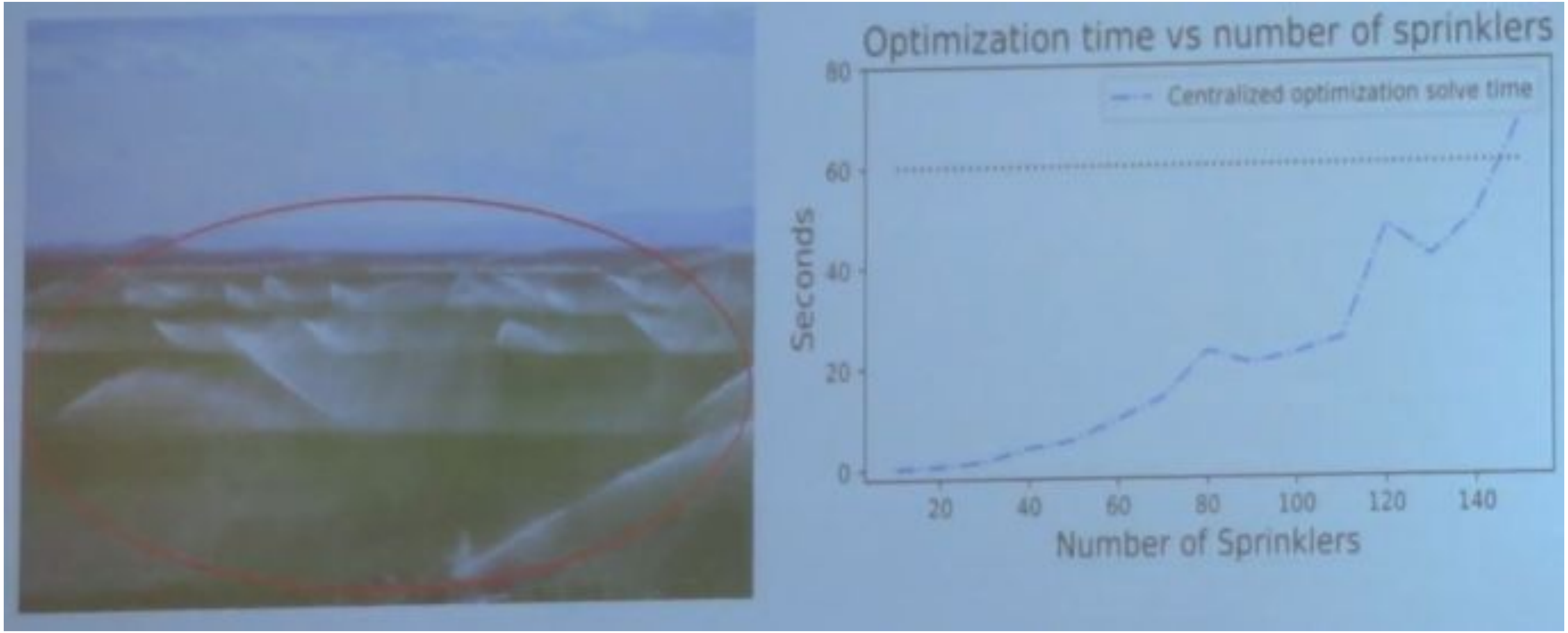
Centralized Control - Controller Redundancy



Centralized Control - Communication



Centralized Control - Performance



WISDOM - Distributed Control

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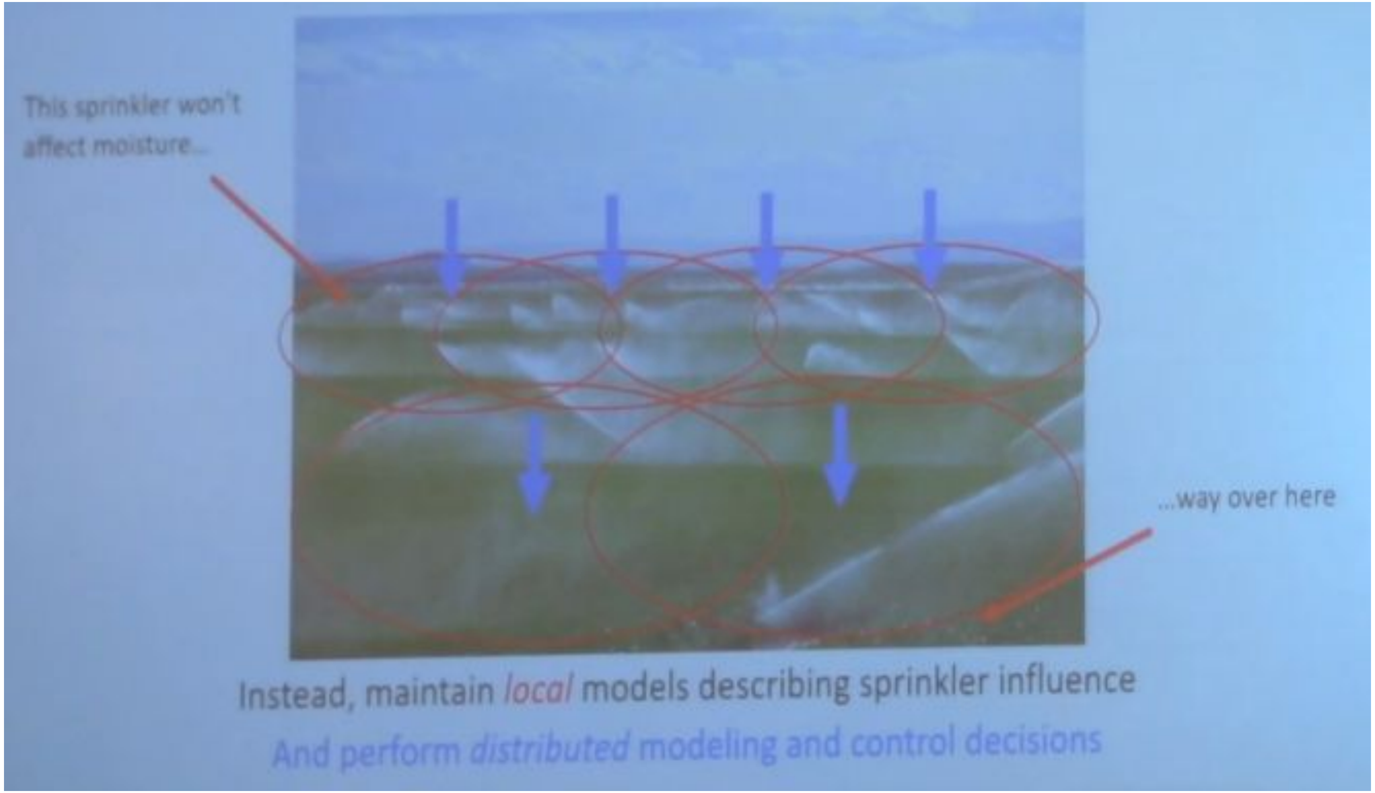
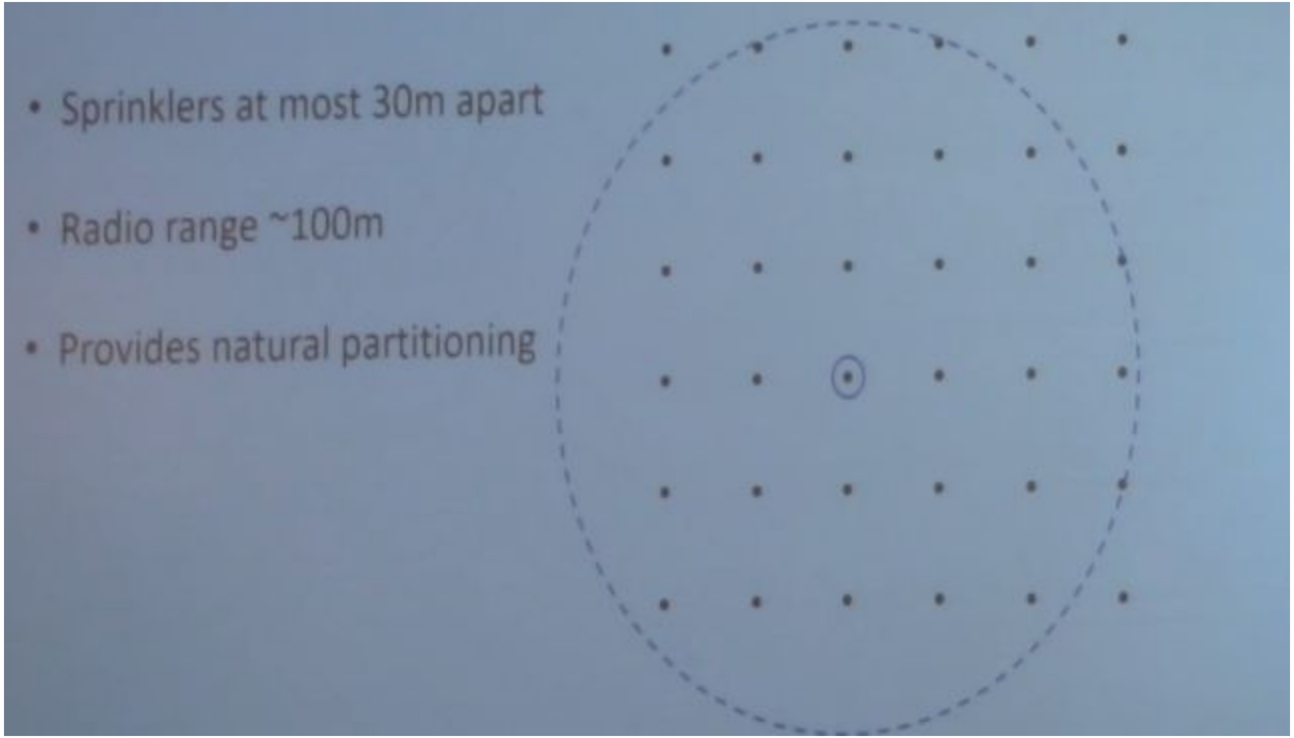


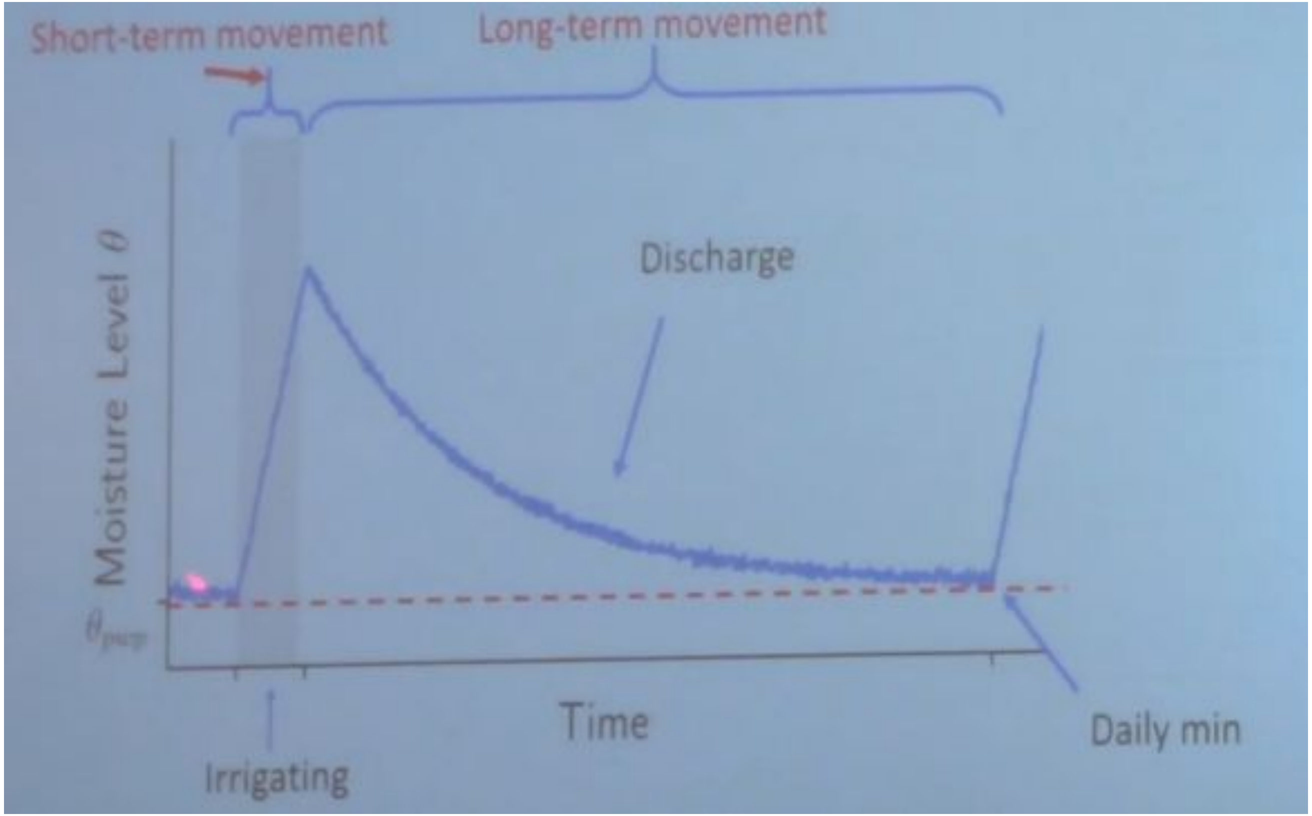
Benefits of Distributed Control

	Centralized Control	Distributed Control
• Remove system's single point of failure at basestation		✓
• Remove *ALL* cross-network traffic (reduce energy, network contention)		✓
• Remove wasteful computational overhead of global modeling		✓

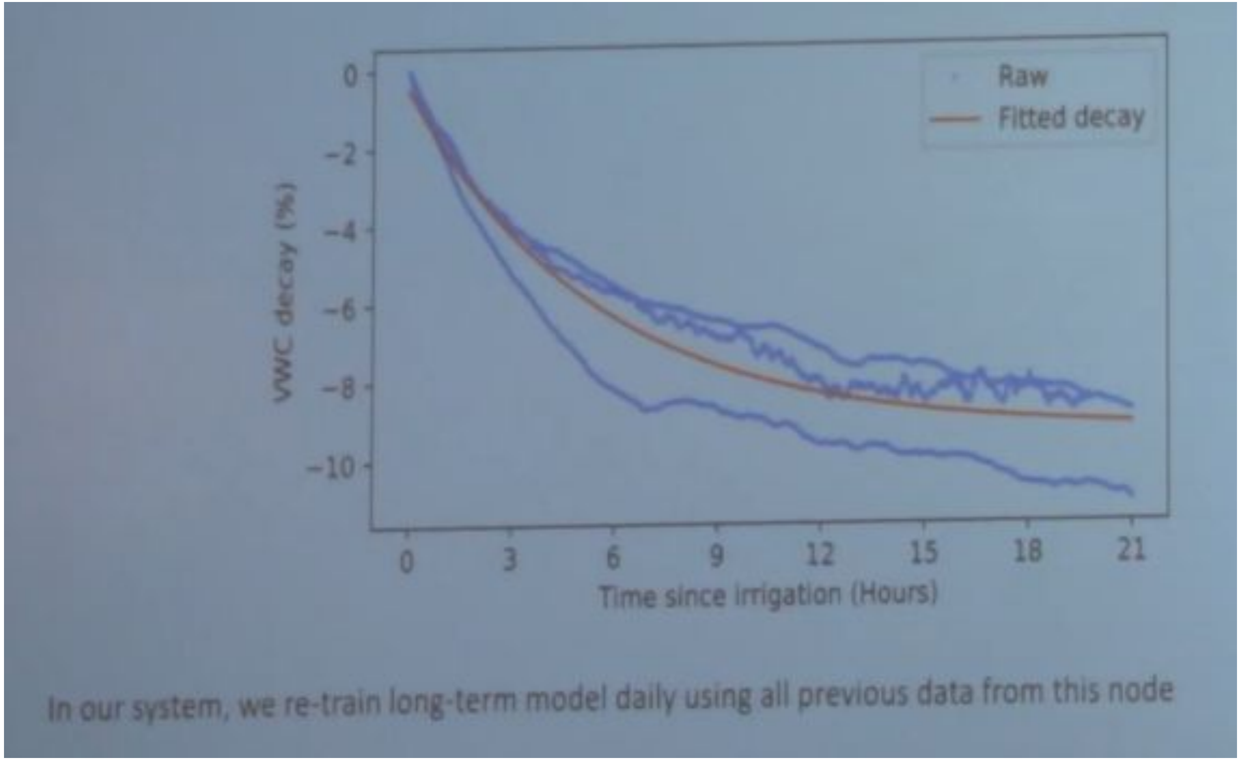
Automatic neighborhood creation/maintenance



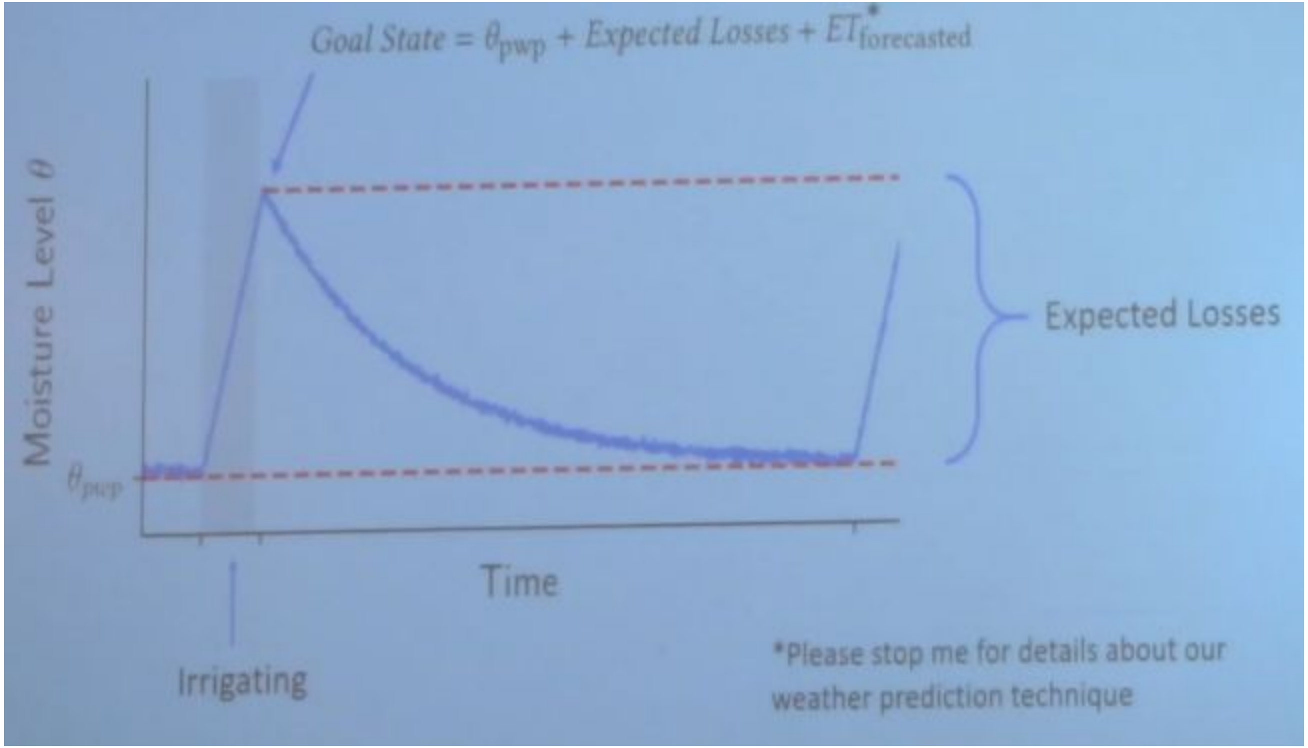
24-hour Soil Moisture Cycle



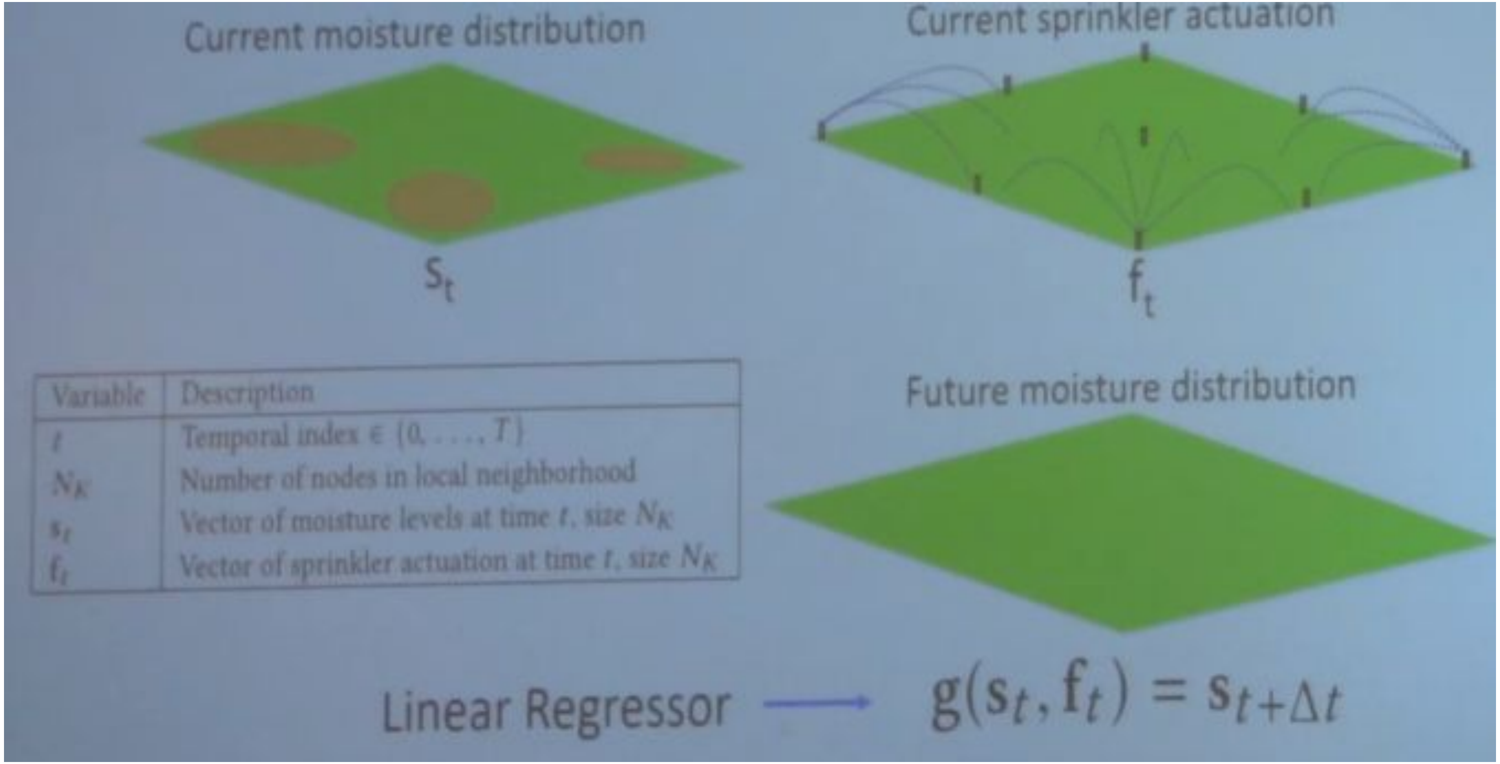
Modeling long-term moisture movement



Modeling long-term moisture movement



Modeling short-term water movement



Finding Optimal Schedules

Variable	Description
t	Temporal index $\in \{0, \ldots, T\}$
k	Sprinkler location index $\in \{1, \ldots, N_K\}$
$\mathbf{s}_t$	Vector of moisture levels at time t, size N_K
$\mathbf{f}_t$	Vector of binary sprinkler actuation at time t, size N_K
$f_{k,t}$	Sprinkler k actuation at time t, $\in \{0, 1\}$
$s_{k,t}$	Volumetric water content (VWC) of location k at time t
c_k	Flow rate of sprinkler k (Constant, known beforehand)
θ_k	Measured VWC of sensor k (Constant, known beforehand)

Table 2: Optimization Variables

$$\min_{\{f_{k,t}, s_{k,t}\}_{k=1,t=0}^{N_K,T}} \sum_{k=1}^{N_K} \sum_{t=0}^{T} c_k f_{k,t} \quad \text{s.t.} \tag{3a}$$

Minimize system water consumption

$$0 \le f_{k,t} \le 1 \qquad k = 1, \ldots, N_K \quad t = 0, \ldots, T \tag{3b}$$

Physical solenoid constraint

$$s_{k,t} \ge \theta_{\text{pwp}} \qquad k = 1, \ldots, N_K \quad t = 0, \ldots, T-1 \tag{3c}$$

Quality of service

$$s_{k,T} \ge \theta_{\text{goal},k} \qquad k = 1, \ldots, N_K \tag{3d}$$

Goal state

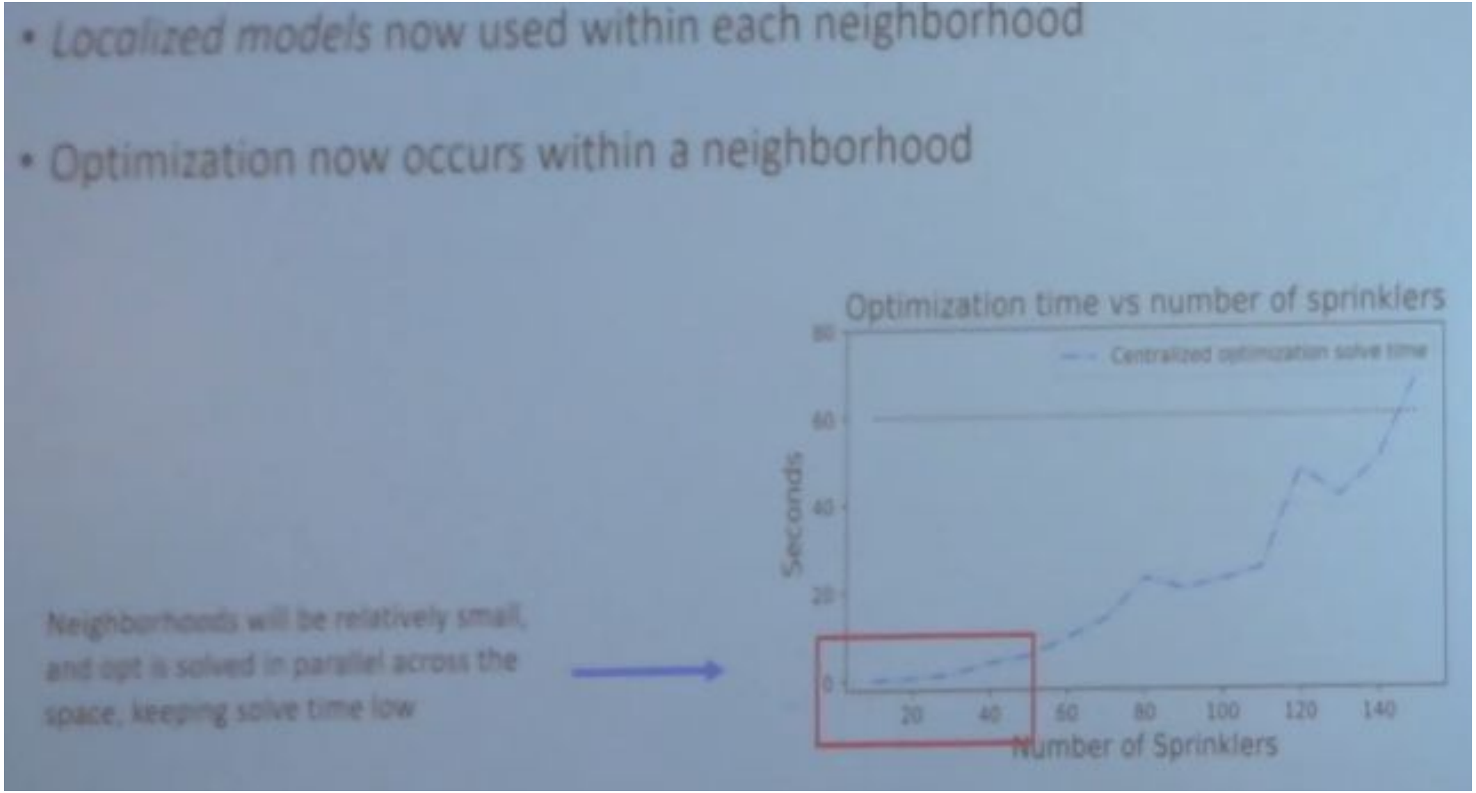
$$s_{k,t=0} = \theta_k \qquad k = 1, \ldots, N_K \tag{3e}$$

Initial moisture measurements

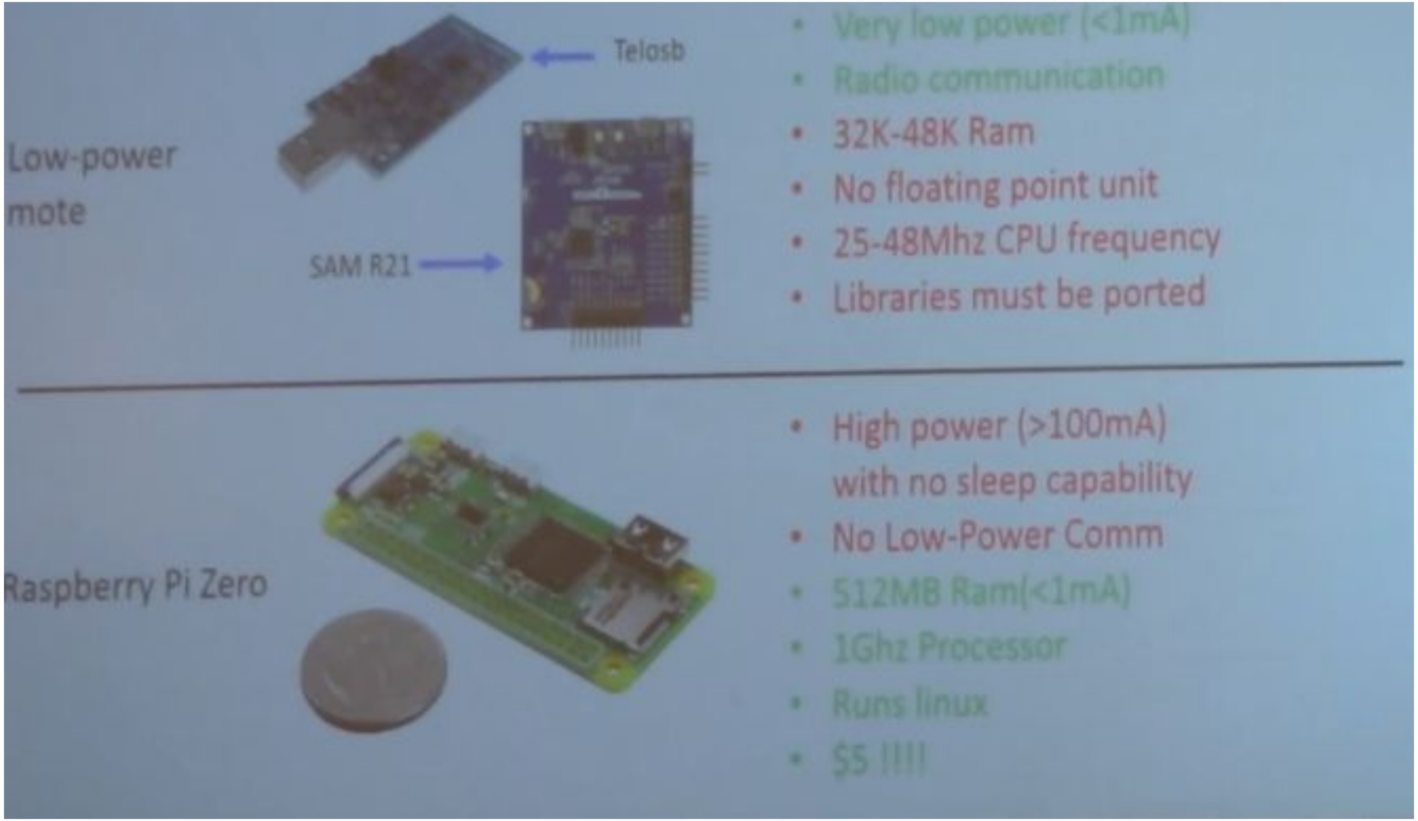
$$\mathbf{s}_t = \mathbf{g}(\mathbf{s}_{t-1}, \mathbf{f}_{t-1}) \qquad t = 1, \ldots, T \tag{3f}$$

Short-term water movement

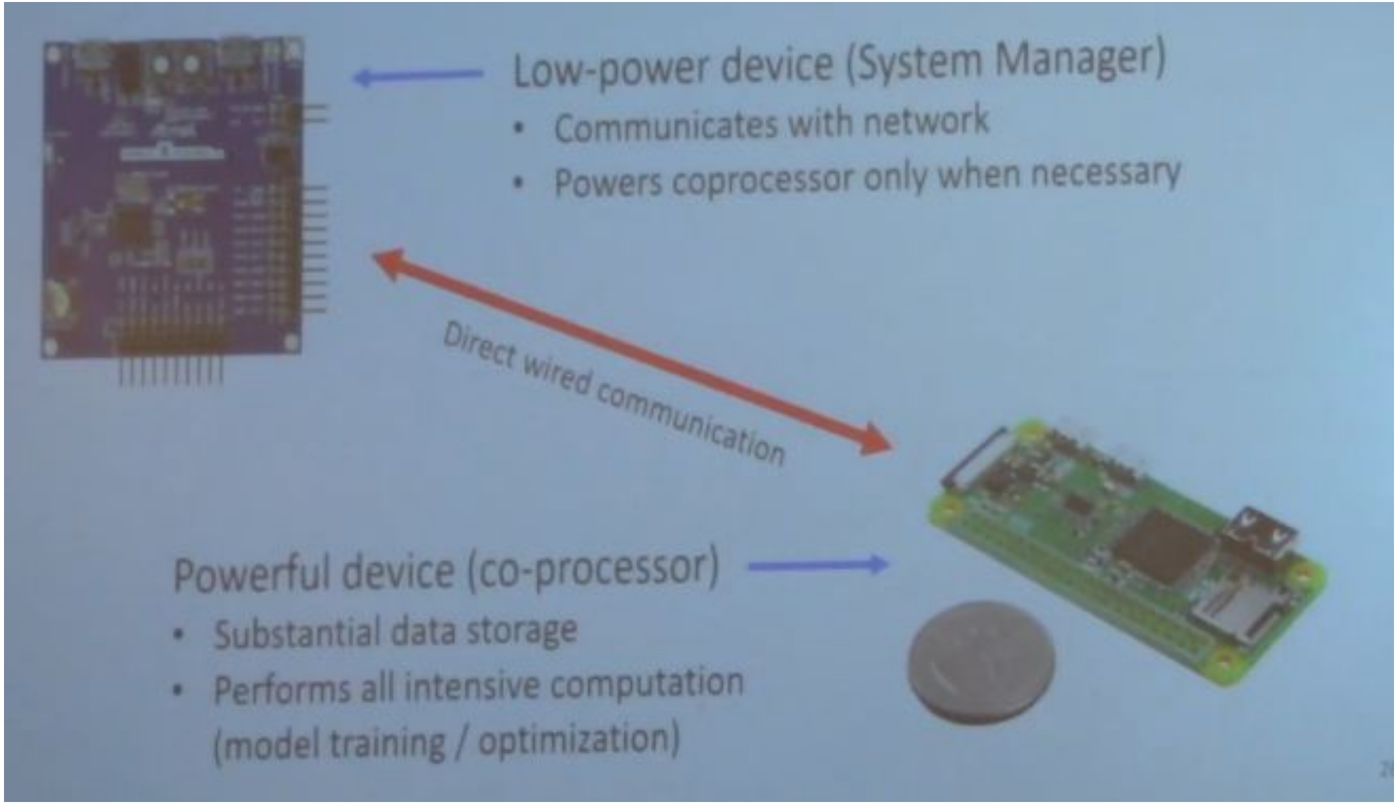
Distributed Processing Pipeline



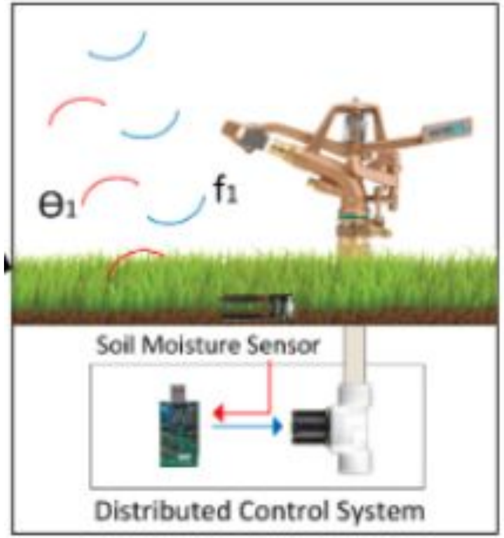
Current hardware platforms are insufficient



WISDOM co-processor hardware architecture



System Lifetime: Energy Harvesting



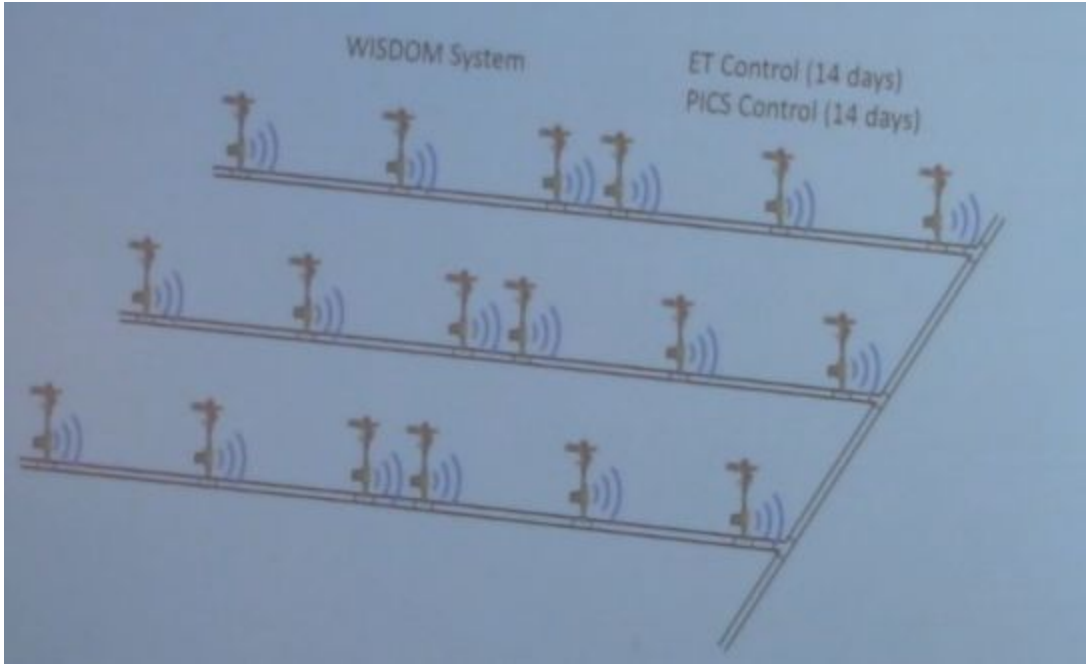
Micro-hydro water turbine enables perpetual system lifetime

WISDOM Contributions

- Distributed control
    - Local modeling and optimization on end devices
    - Data communication only required between neighbors
    - New co-processor architecture to facilitate distributed computation
    -
- Energy harvesting enables perpetual system operation

Case Study

Case Study



ET: centralized + industrial state-of-the-art
PICS: centralized + data-driven
WISDOM: distributed + data-driven

Results - Case study vs ET

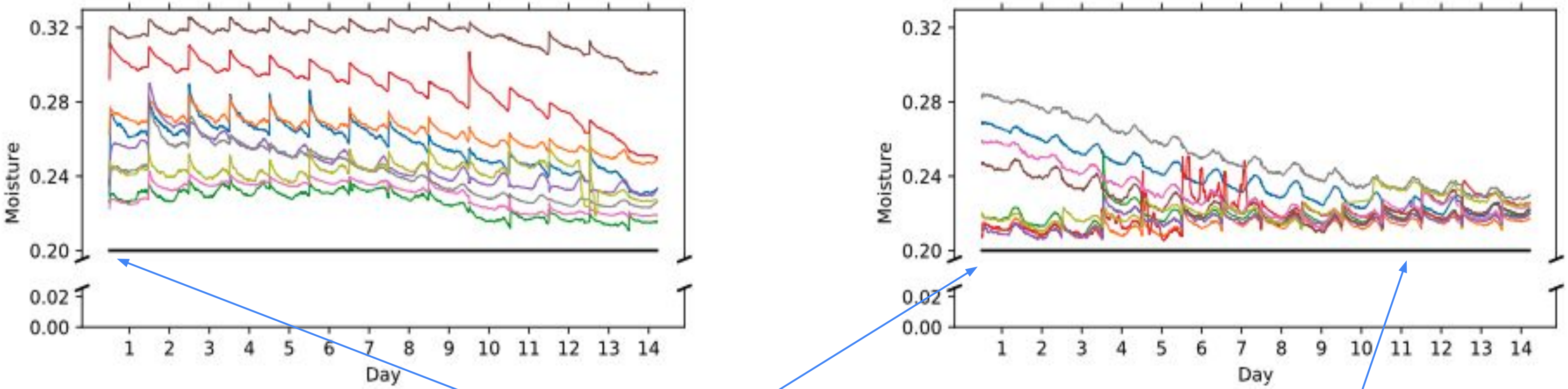


Figure 5: Collected VWC data across deployment for all Evapotranspiration (left) and WISDOM (right) nodes

Initial moisture conditions

System approaches steady state

Results - Case study vs ET

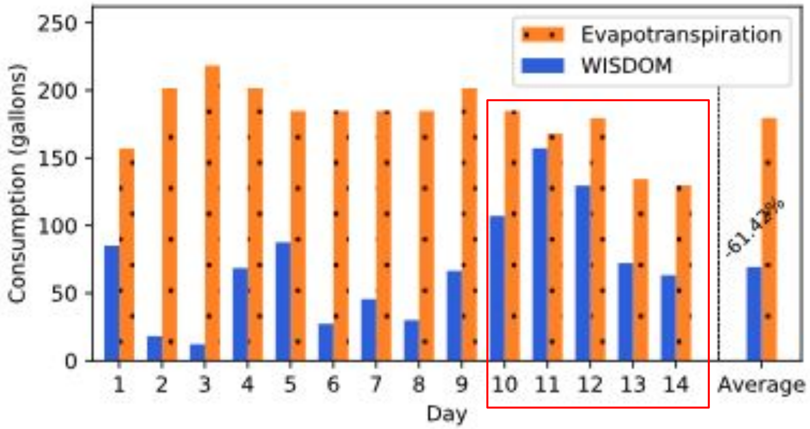


Figure 7: Water consumption of ET vs WISDOM

32.9%

Results - Case study vs PICS

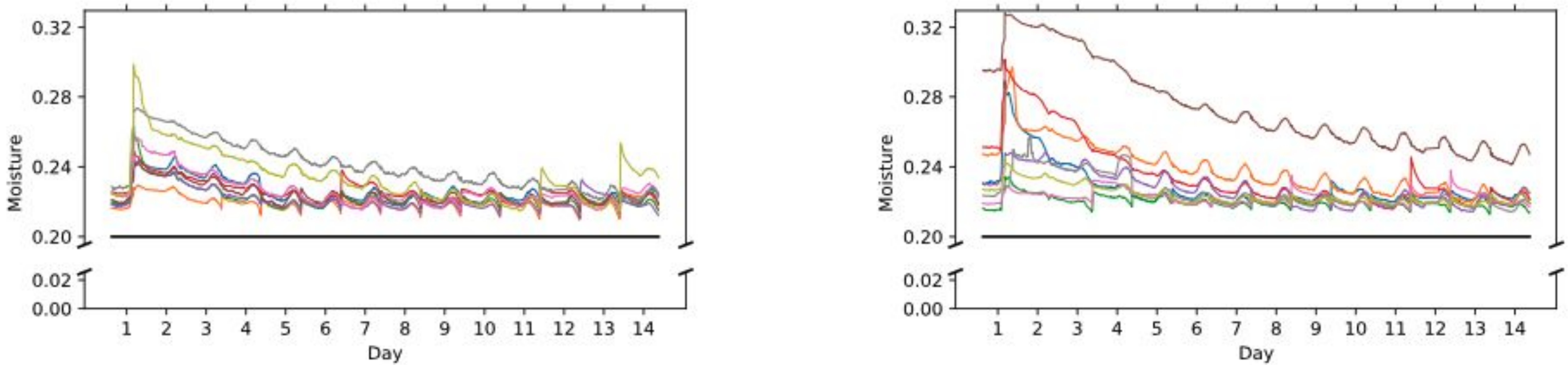


Figure 6: Collected VWC data across deployment for all PICS (left) and WISDOM (right) nodes

Results - Case study vs PICS

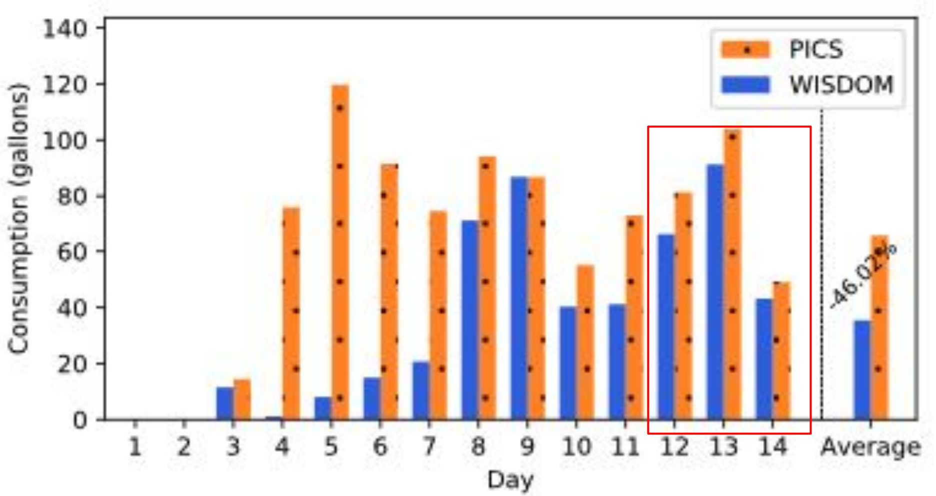


Figure 8: Water consumption of PICS vs WISDOM

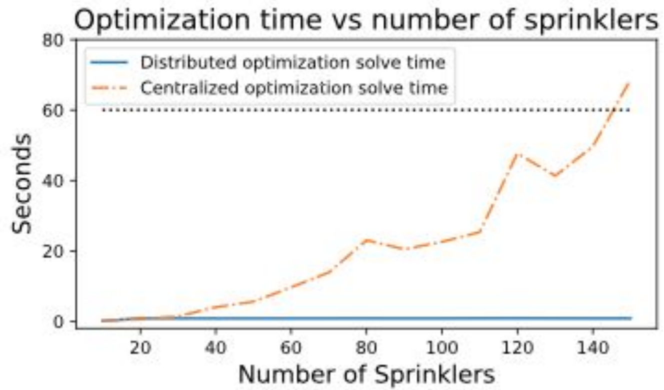


Figure 14: Time required to optimize schedules using centralized (PICS) and distributed (WISDOM) systems

Within 4% of each other

Economic Analysis

Component	WISDOM	PICS [40]
Mote (includes M & A costs for WISDOM)	$25.00	$37.57
Raspberry pi zero	$5.00	–
Battery and charge circuit	$21.00	$4.00
Harvesting turbine	$12.00	–
Sealed enclosure	$13.00	$10.00
Moisture sensor	$99.00	$110.00
Latching solenoid	$14.00	$15.00
Manufacture and Assembly (only for PICS)	–	$10.00
	$189.00	$186.57

Table 3: Sprinkler Node Manufacture Cost Comparison

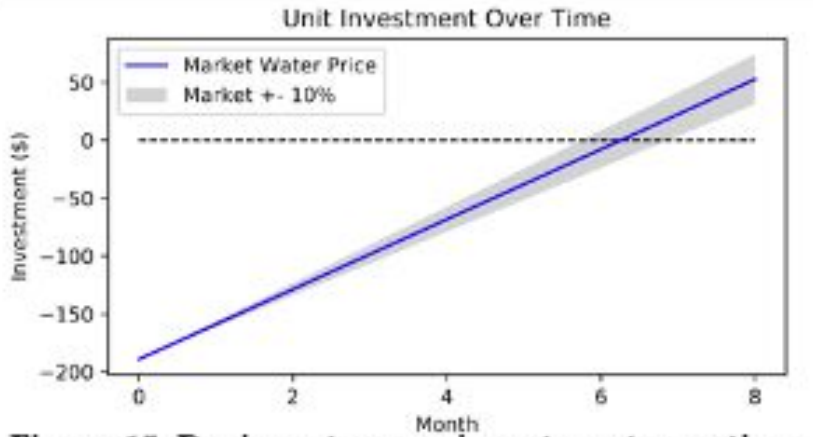


Figure 15: Device return on investment over time

Conclusions

- All QoS and efficiency benefits of PICS
- Distributed system removed limitations of previous work
  - Single point of failure
  - Communication problem
  - Performance
  - True scalability
- Energy harvesting allows perpetual system lifetime
- Flexible new hardware platform enables in-network computation

Backup

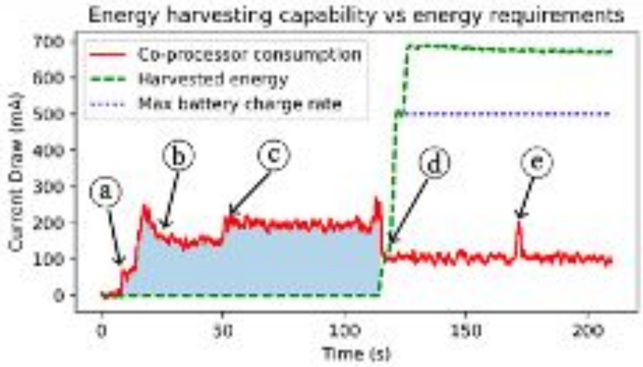


Figure 3: Node energy profile across (a) boot, (b) Julia initialization, (c) first optimization solve, (d) completion and return to idle, and (e) subsequent optimization

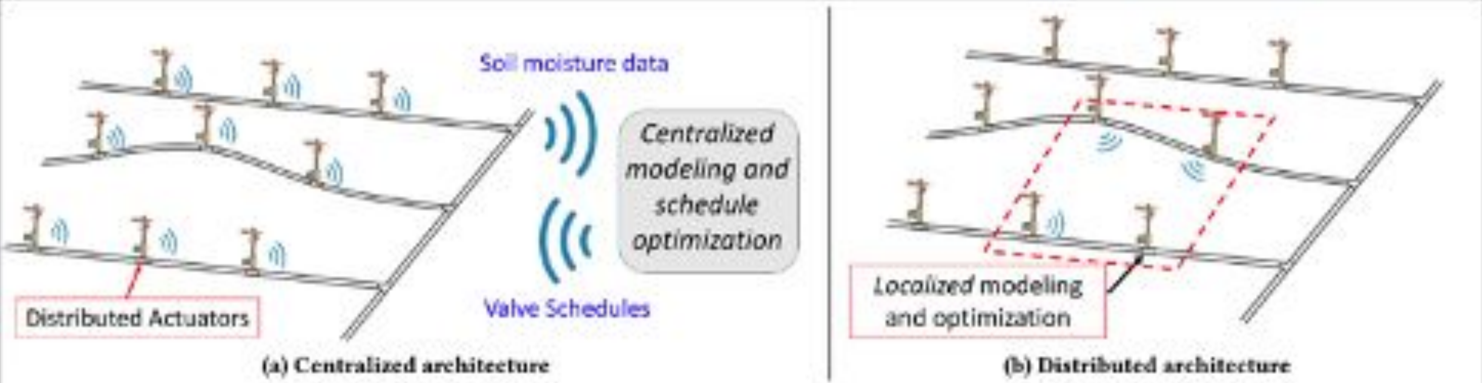


Figure 1: Comparison of PICS (left) and WISDOM (right) system architectures