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Water Distribution System Sensors and Sensor Networks

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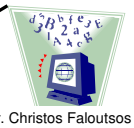
Domain Knowledge **Database Expertise**



Managing Environmental Data Sensing

Decision-Making

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Jure Leskovec

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Outline

- Drinking Water Distribution Systems
- Security Issues
- Available Sensors
- Sensor Networks
- Integration of Sensors into SCADA
- Sensor Placement Optimization

set-up

research challenges

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Drinking Water Systems

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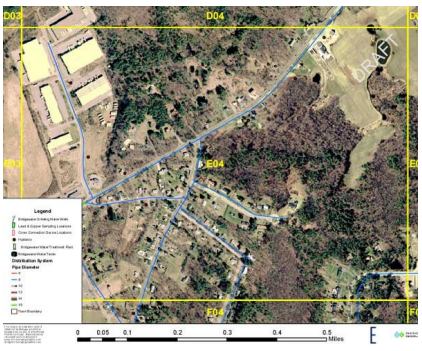

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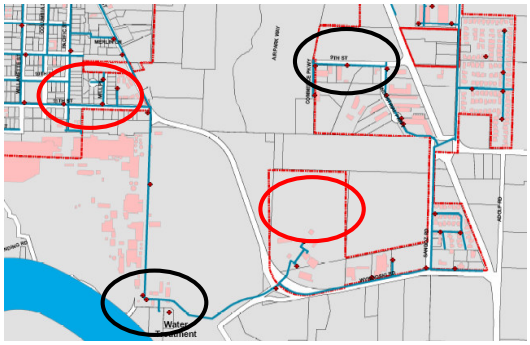

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Drinking Water Security

- The Homeland Security Presidential Directives (HSPDs) and the Public Health Security and Bioterrorism Preparedness and Response Act (Bioterrorism Act) of 2002 specifically denote the responsibilities of EPA and the water sector in:
- Assessing vulnerabilities of water utilities
- Developing strategies for responding to and preparing for emergencies and incidents
- Promoting information exchange among stakeholders
- Developing and using technological advances in water security

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Drinking Water Security

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Securing the Water Supply

- Prevention
  - limit access and secure critical infrastructure
  - Implement control measures to evaluate security and access restriction
  - Vigilance

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Securing the Water Supply

- Prevention
  - limit access
  - Implement control measures to evaluate security and access restriction
  - Vigilance

- Detection
  - Develop methods to identify intrusion events and detect specific agents
  - Evaluate vulnerabilities to place detectors at optimal locations to minimize effects following an intrusion
  - Understand uncertainties

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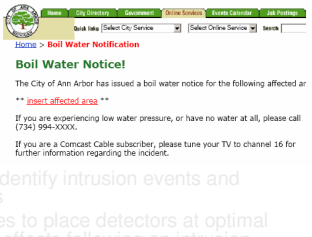
Securing the Water Supply



- P
- D
  - identify intrusion events and
  - s to place detectors at optimal locations to minimize effects following an intrusion
  - Understand uncertainties
- Response

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Detection Focus: Objectives

- Develop drinking water quality models for distribution systems that allow prediction and evaluation of multiple potential chemical and biological threats
- Determine spatial and temporal resolutions necessary for *in situ* data collection sensor networks for real-time decision-making
- Improve methods for handling and interpreting real-time streaming data from *in situ* sensor networks.

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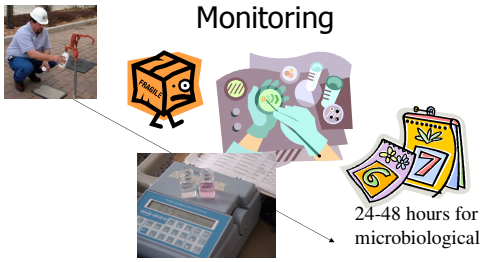
Detection: Current Distribution System Monitoring



24-48 hours for microbiological

Minutes for chlorine

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Sensors for Water Distribution Systems

Biosensors

- False Positives
- Neither Continuous nor Instantaneous
- Often require reagents
- Unacceptable sensitivity
- Often requires pretreatment
- Not robust

Other Sensors

- Chlorine
- Total Organic Carbon
- Failure sensors
- pH
- Temperature
- Flow

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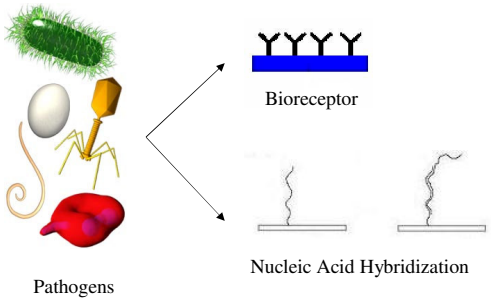
Sensors Targeting Pathogens



Pathogens

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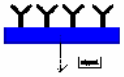
Schematic Diagram of General Biosensor

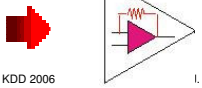
Target Analyte

Bioreceptor

Transducer



Data Acquisition, Amplification and Processing



Output

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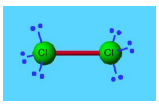
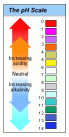
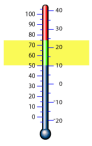
Sensors Available for On-Line Use in Water Distribution Systems



Chlorine

Turbidity





Temperature

- Total Organic Carbon
- Dissolved Oxygen
- Conductivity

pH

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USEPA Believes Chlorine Sensors May be Used as Surrogates to Biosensors

"monitoring assures proper residual at all points in the system, helps pace re-chlorination when needed, and quickly and reliably signals any unexpected increase in disinfectant demand. A significant decline or loss of residual chlorine could be an indication of potential threats to the system."

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Hach 9184 Free Chlorine Analyzer

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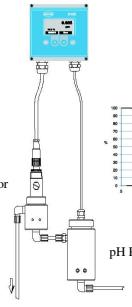
Hach 9184 Free Chlorine Analyzer

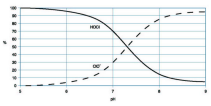
Reaction at Cathode
$HOCl + H^+ + 2e^- \rightarrow Cl^- + H_2O$

Reaction at Anode
$2Cl^- + 2Ag^+ \rightarrow 2AgCl + 2e^-$

Amperometric Sensor
Temperature Probe



Free Cl = $HOCl + OCl^-$



pH Probe

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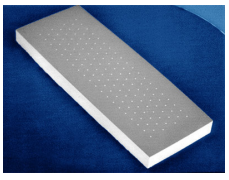
Operation of Chlorine Sensors

15 micron diameter microdisc



137 discs on
2.8 X 7 X 0.5 mm chip

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Operation of Chlorine Sensors

Benefits of Microelectrodes

- Response independent of convective regime, pressure, or pH
- Miniature construction allows for in-situ installation in water lines
- Reagentless
- Detection limit of 0.02 ppm

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Chlorine Sensors

Locations for chlorine sensors and why:

- Representative locations within the system
  - As required by the SDWA and recommended as a best management practice
- Dead ends or low flow/pressure zones
  - Often low flow and therefore low chlorine residual. Not as much of a concern in water security because the hydraulics of the system in these locations do not favor widespread circulation of any contaminant
- Aged pipe segments
  - Corroded pipe interiors promote biofilm attachment and growth and typically results in increased chlorine demand.

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Commercially Available Cl Sensors

Maker	Sensitivity (mg/L)	Operation Method	Cost
Hach CL 17	0.035	Colorimetry	$3,000
Hach Accuchlor	0.01	Electrode	$3,400
Teledyne Orbit	0.01	Electrode	N/A
Au-Sensys	0.02	Microelectrode	N/A

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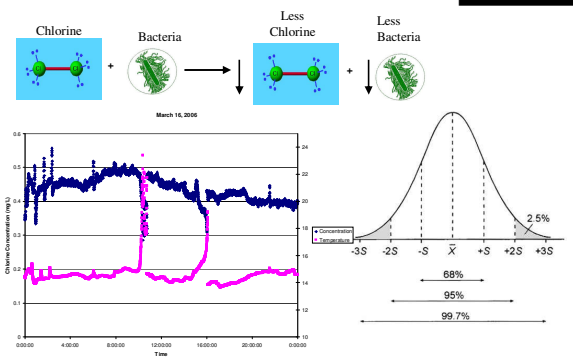

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TOC Sensors

- TOC is a measure of organic fraction of dissolved or suspended particles in aqueous solution
- Application in water security: sudden change in the TOC could indicate the presence of a toxic, biological contaminant
- Does not identify the nature of any *specific* biological threat, but could act as an indirect measurement of the water's quality and a potential biological threat

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TOC Sensors

- Operate by oxidizing organic carbon to CO_2 and measuring the CO_2 generated
- Oxidation step may be performed at high or low temperature
- CO_2 quantification in sensors typically by noninfrared dispersion or colorimetric methods

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Failure Detection Sensors

- Measures opacity of the water
- Opacity constant in water distribution systems, but may increase upon a pipe burst, flushing, or a sudden pressure change
- An intentional introduction of a chemical or biological event would likely require a pump that would introduce a significant pressure gradient into the system that may be detectable by this type of sensor
- Sensor design is robust and low cost (~$5.00)
- Designed and deployed in a water distribution in Bradford, England

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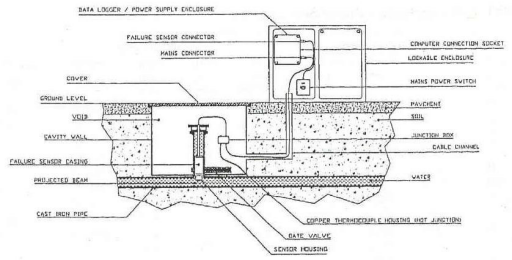
Failure Sensors



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Acoustic Leak Detection Sensors

- **The American Society of Civil Engineers estimates 6 billion gallons of treated drinking water are being lost daily through leaking pipes like this one.**

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Detection: What about integrated multi-analyte and real-time?

Is detection sufficient?

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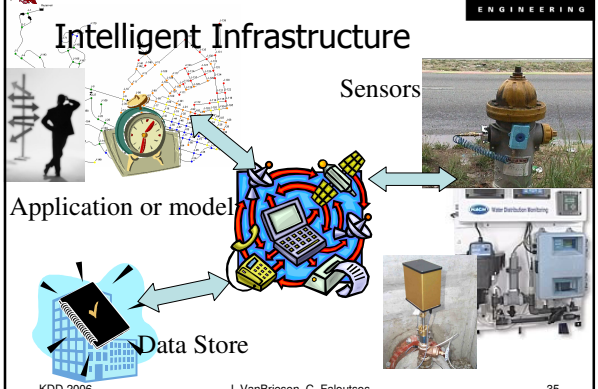
Intelligent Infrastructure



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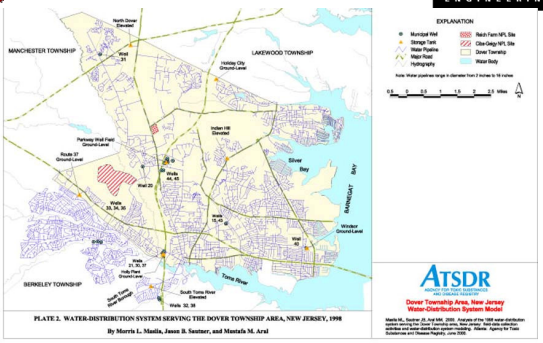

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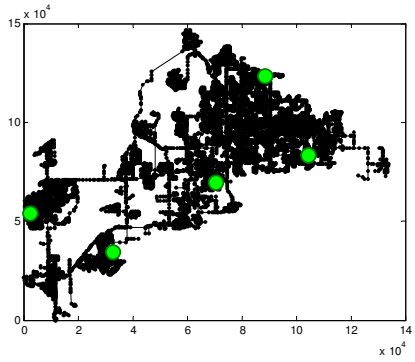

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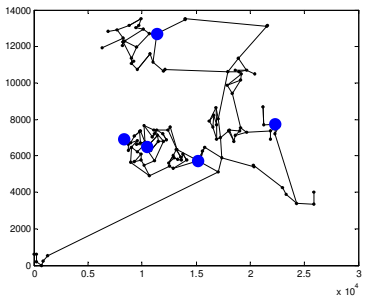

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Drinking Water Sensor Networks: what are the issues?

- Hardware – expensive, uses consumables, power requirements, cannot have 100% network coverage.
- Handling Data – too much data, sorting through what it all means in real-time, finding patterns
- Data Quality – false positives and false negatives, surrogates and undetectable contaminants
- Response – short term alerts, shifting to other water sources, bringing the system back on line, re-establishing consumer trust.

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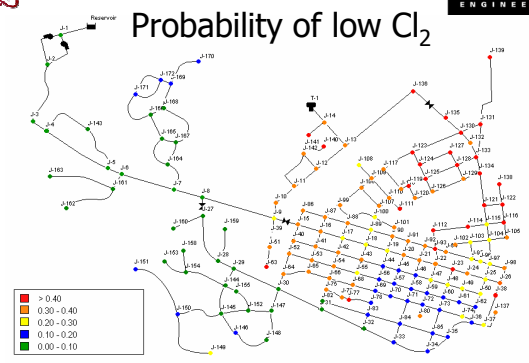
Probability of low Cl_2



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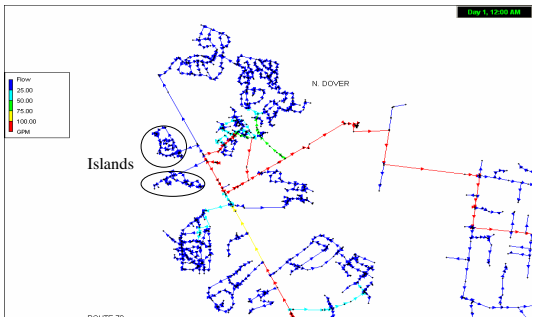

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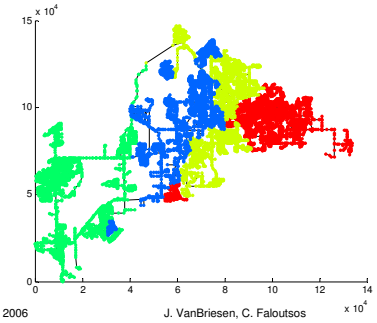
Decomposition of Network



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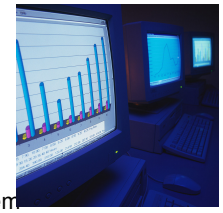
Sensor Data

- Function
- Management Methods
  - Database Systems
  - SCADA
  - Selective Monitoring System



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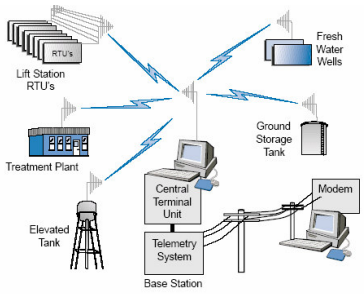
SCADA



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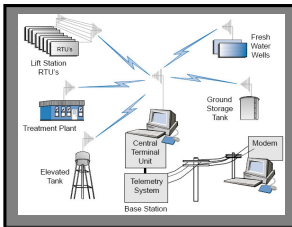
Expanding SCADA Systems for Sensor Data

Data Collection

Modeling (EPANET Toolkit)

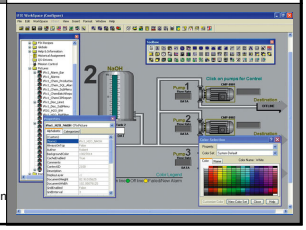
SCADA

- Real-time data management
- Real-time system control
- Monitoring/Modeling w/2+ parameters



- SCADA objectives
  - Remote Monitoring
  - Remote Operations Control
  - Data Management & Storage
  - Alarm System

- SCADA objectives
  - Regulatory compliance
  - Operation streamlining with automation
  - Provide overall view of system from central location



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SCADA – Data Collection

- Grab-sampling
  - detect contamination events w/ long-term consequences
- Sensors
  - detect short-term, intense contamination events

Routine Monitoring Requirements

	Coverage	Monitoring Frequency	Compliance
TTHM/HAA5	Surface and ground water under the direct influence of surface water serving ≥ 10,000	4/plant/quarter	Running annual average
	Surface and ground water under the direct influence of surface water serving 500 - 9,999	1/plant/quarter	Running annual average
	Surface and ground water under the direct influence of surface water serving < 500	1/plant/year in month of warmest water temperature**	Running annual average of increased monitoring
	Ground water serving ≥ 10,000	1/plant/quarter	Running annual average
	Ground water serving < 10,000	1/plant/year in month of warmest water temperature**	Running annual average of increased monitoring
Bromate	Ozone plants	Monthly	Running annual average
Chlorite	Chlorine dioxide plants	Daily at entrance to distribution system; monthly in distribution system	Daily/follow-up monitoring
Chlorine dioxide	Chlorine dioxide plants	Daily at entrance to distribution system	Daily/follow-up monitoring
Chlorine/Chloramines	All systems	Same location and frequency as TCR sampling	Running annual average
DBP precursors	Conventional filtration	Monthly for total organic carbon and alkalinity	Running annual average

** System must increase monitoring to 1 sample per plant per quarter if an MCL is exceeded.

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SCADA – Modeling Integration

- Disaster response preparedness
- Simulating historical events
- Predicting future conditions
- Initialization & calibration of model
- Controlling systems w/real time sensor data
- Modeling more than one component / Toolkit

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Selective Monitoring Systems

Causal Reasoning:

Sensitivity Analysis

1. Define value of change
2. Simulate forward
3. Sum all value changes
4. Rank sensors

Cascading Alarm Analysis

1. Define alarm state
2. Simulate forward
3. Sum all alarm states
4. Record paths
5. Rank sensors

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Selective Monitoring Systems

Sensor selection

- Approach of determining the most informative subset of sensor data
- Draws on information theory and causal reasoning concepts

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BWSN Competition

- **Z4:** detection likelihood. *For a given sensor network design*, the detection likelihood is defined as # events detected/# contamination events tested. For ANY particular contamination event Z4 is 1 or 0 (detected or not) but for any network design Z4 requires summing all the 1 or 0 values for the contamination events.
- **Z1:** expected time to detection. Minimum detection time *for the sensor network* and a particular contamination event is the minimum detection time among ALL sensors present in the design. Detection is any nonzero concentration.
- **Z3:** Expected demand of contaminated water exceeding hazard concentration prior to detection. *For a given time to detect (determined by the sensor locations)*, and a particular contamination event, water consumed at all nodes with a concentration > 0.3 mg/L from the event time to the detection time (Z1) is summed to determine Z3.
- **Z2:** Expected population affected prior to detection. For a *given time to detect (determined by the sensor locations)* Z1 determines the critical time that determines the end point of mass ingested. Mass ingested is computed from concentration and water demand at each node at each time step prior to the detection time. This is used to determine the probability that a person who ingests a given contaminant mass will become infected. This is used to determine the affected population in each contamination event.

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Computing Scores

- Given a placement (set **A** of nodes)
- For each scenario **i**
  - Look up detection time **Ts** for each sensor **s 2 A** in Table 1
  - Compute detection time for **A** as **TA = min(Ts | s 2 A)**
  - If not detected, set Z4 to 0, assign penalty to Z1, Z2, Z3
  - Otherwise, Z4 = 1.
    Look up cumulative value of Z2 and Z3 at time **TA** from Table 2.
- Sum Z1 … Z4 over all scenarios to get final score

- Need to store per scenario:
  - Time of detection per sensor (· 51 KB, usually 5 KB)
  - Z2/Z3 values per simulation timestep (· 5 KB)
  - Can evaluate **any sensor placement** quickly using only this summary information! ☺

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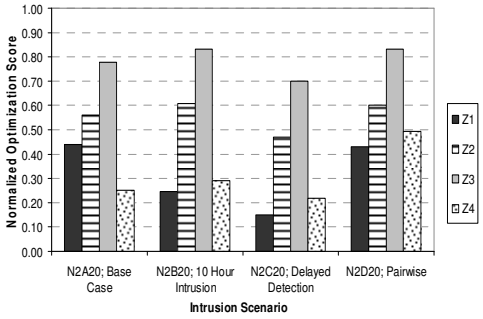

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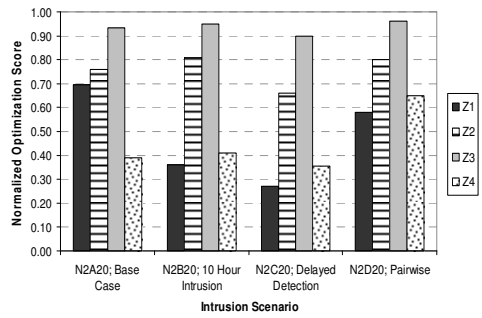

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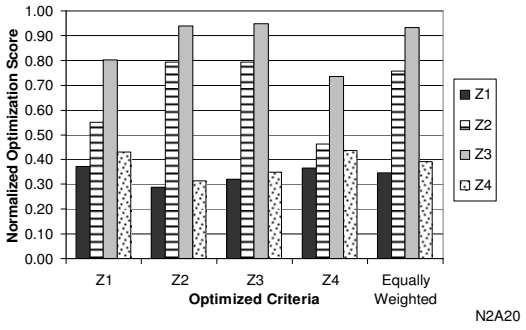

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Take Home Messages

- Distribution system is open and accessible, but effect of attack is difficult to predict
- Most sensors monitor surrogates (1 or more)
- Most sensors are very expensive
- Deployment with less than 1% coverage will generate lots of data but *directly* detect few attacks.
- New optimization plans for placement must be considered (e.g., maximize detection of catastrophic attacks or protect critical assets).
- New methods to manage and interrogate the data must be developed to improve the "detection" rate by using network dependent information beyond the binary response of individual sensors.

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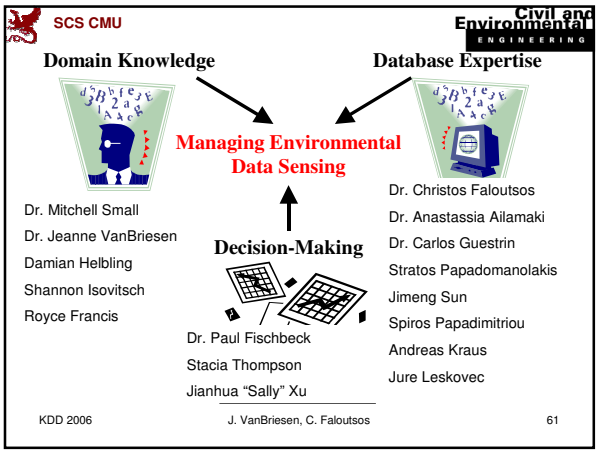
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