Communication Pattern Anomaly Detection in Process Control Systems

Alfonso Valdes
Steven Cheung

SRI International

Sponsored by the Department of Energy National SCADA Test Bed Program
Managed by the National Energy Technology Laboratory
The views herein are the responsibility of the authors and do not necessarily reflect those of the funding agency.

Securing Process Control Systems

- **Digital controls are essential to modern infrastructure systems**
- **Migration from proprietary systems to commodity platforms, TCP/IP and other common standards, connection to corporate IT**
  - Significant gains in productivity, inter-operability
  - Increasing exposure to cyber attack?
- **Best practice architectures call for perimeter defenses**
  - Increasingly diffuse electronic perimeter
- **Intrusion Detection provides a necessary complementary defense**

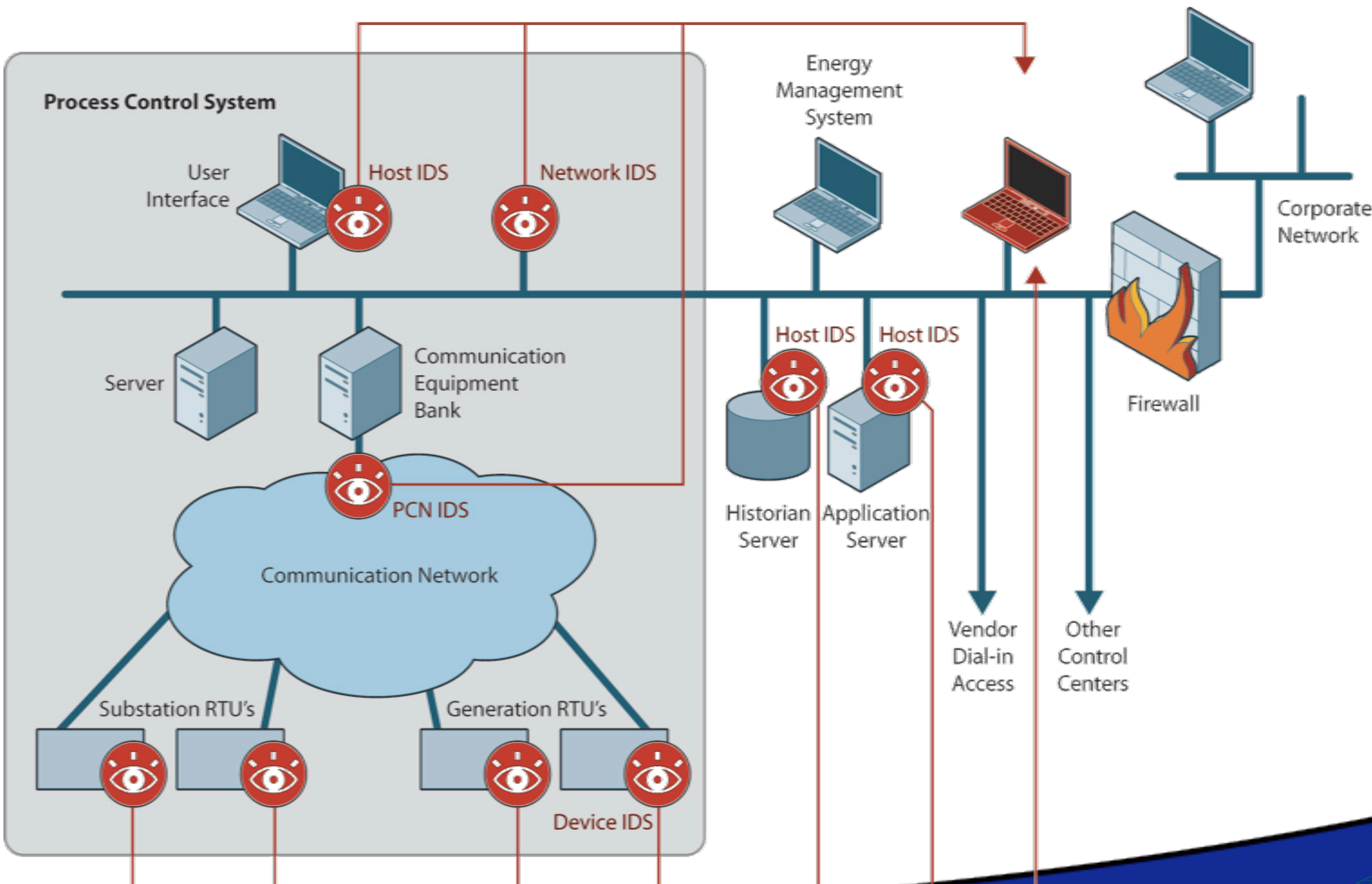
DATES Vision

- Future control systems with PCS aware defense perimeter
- IDS systems fully tuned for control system protocols and highest threat attacks
- Realtime event correlation system for threat identification and response
- Developed in partnership with leading SIEM and PCS providers
- Demonstrated on realistic PCS implementations

Intrusion Monitoring as Part of Defense in Depth

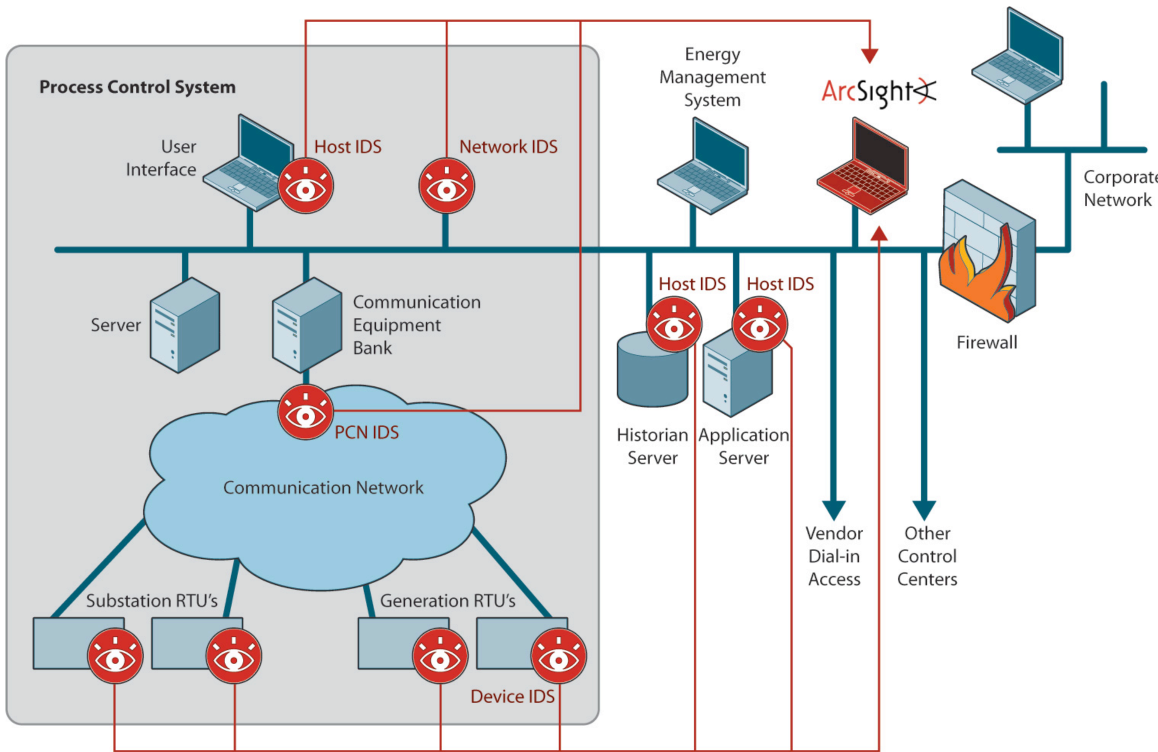
- **Control Systems use perimeter defenses**
  - Firewalls, switches
  - Network segmentation
  - DMZ between control and business networks
- **Why monitor?**
  - Ensure perimeter defenses are still effective (Configuration Drift)
  - Ensure perimeter defenses are not bypassed (Out of band connections, dual ported devices—What's on YOUR Field LAN?)
  - Ensure perimeter defenses are not compromised (Attack on the firewall itself)
  - Be aware of unsuccessful attempts to penetrate

High Level Monitoring Architecture

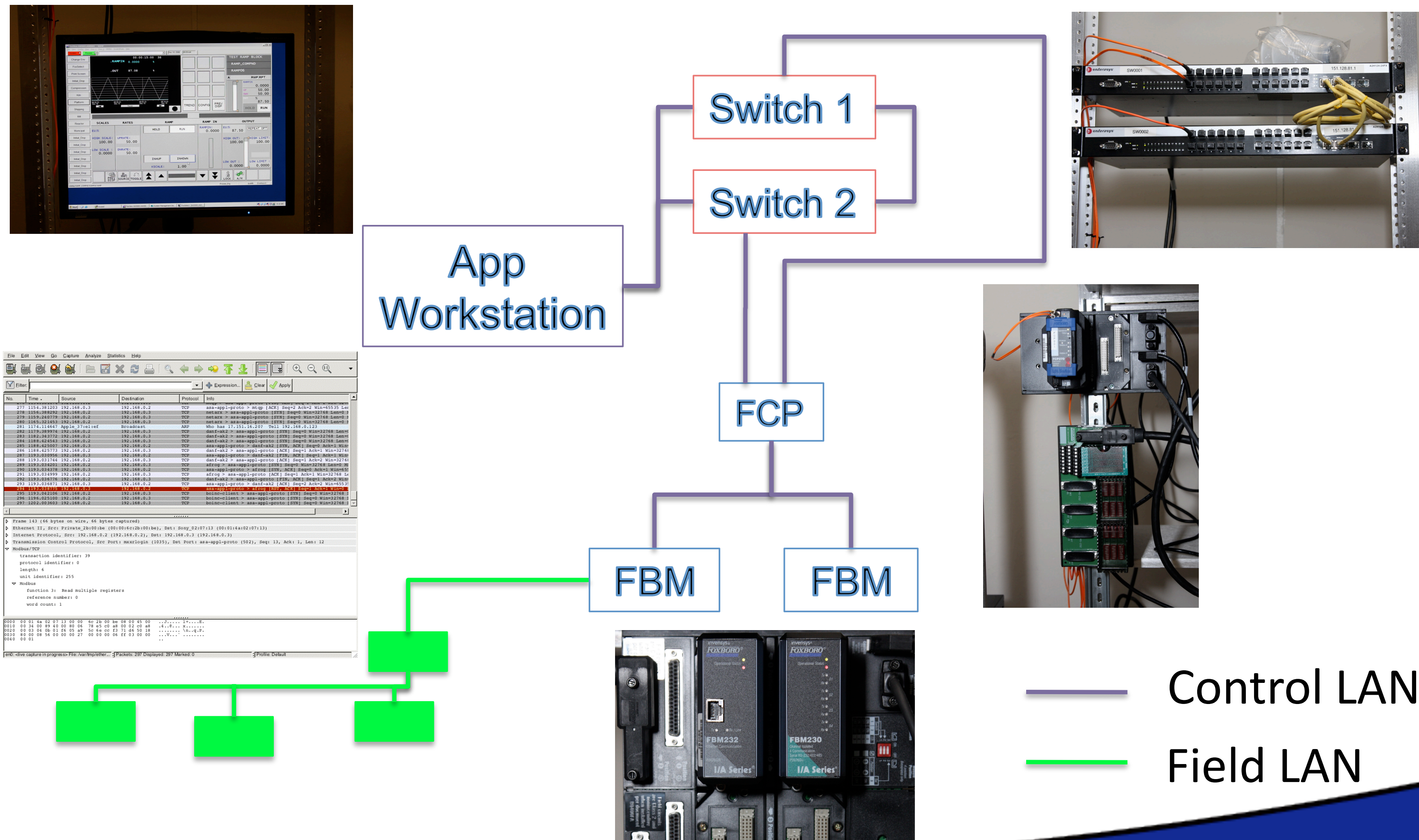


Detection and Event Management

- **Control System aware IDS at the Device, Control LAN, and Host**
- **Event Correlation integrates new detection data sources into ArcSight**
- **Result:**
  - Correlate attack steps
  - Follow an attack across LAN segments



Test System Diagram (SRI/Invensys)



Detection Strategies

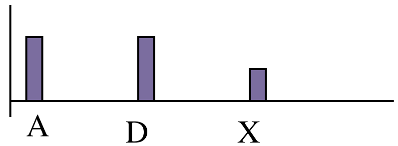
- **Signature: Look for known misuse**
- **Model Based**
  - Note regularities in PCS traffic
  - From configuration to rules
  - Machine learning of comm patterns, master/slave, temporal dynamics
  - Encode a model of expected behavior
  - Alert on exceptions
- **Specification**
  - Based on formal analysis of a protocol, or a particular implementation of a protocol
- **Deep process awareness**

Anomaly Detection Based on Learning

- **Observe the traffic of interest**
- **Learn patterns of normal behavior**
  - Requirement for attack-free training data?
- **After learning, alert on traffic that is extremely unusual**
  - Is the unusual malicious?
  - Is the malicious unusual by the particular statistical characterization
- **Plus: Defense against novel attacks**
- **Minus: High False Positive (FP) rate in practice**

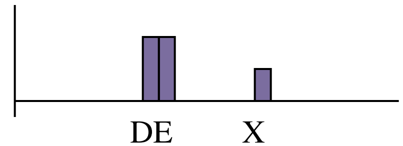
Pattern Learning Through SOM

New Obs

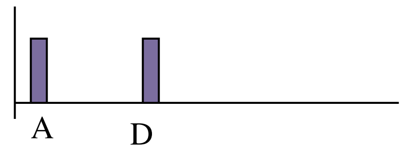


Library patterns

P1

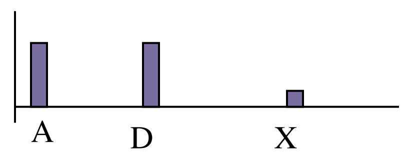


P2



- Observation matches P1 in D and X, P2 in A and D, but X has a low hit count
- => P2 is a better match
- Observation is assigned the label of P2
- Depending on whether P2 is rare or previously labeled malicious, generate an alert
- New P2 has a little “X”
- Does not require attack-free training data

P2



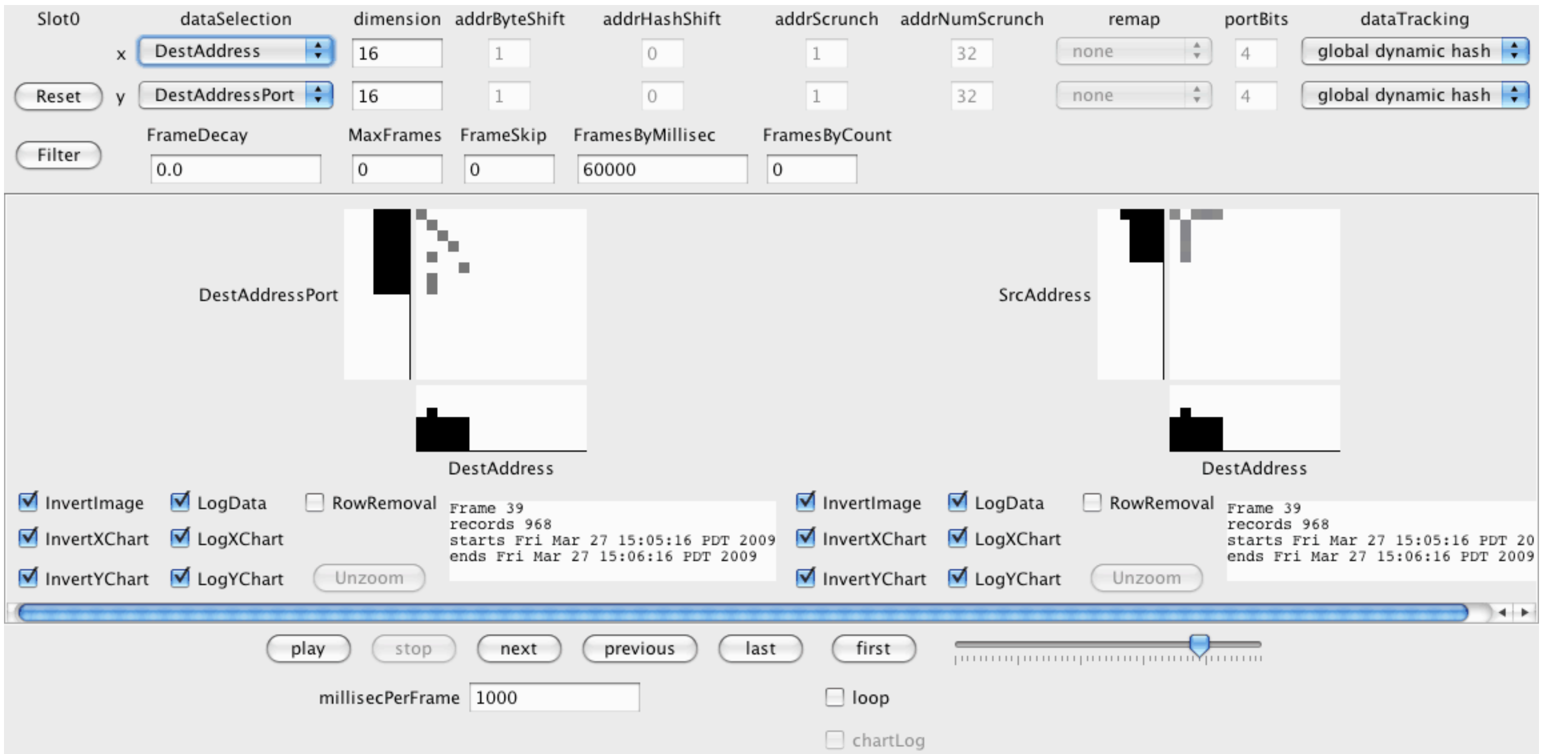
Flow Anomaly Detection

- Observe flows between various nodes in field and control LANs
- Build statistical profile of expected flow frequencies in a given time interval
- Alert when observe new flow or unusual behavior in a known flow
- Alert on the absence of an expected flow
- FP Rate based on estimated flow statistics

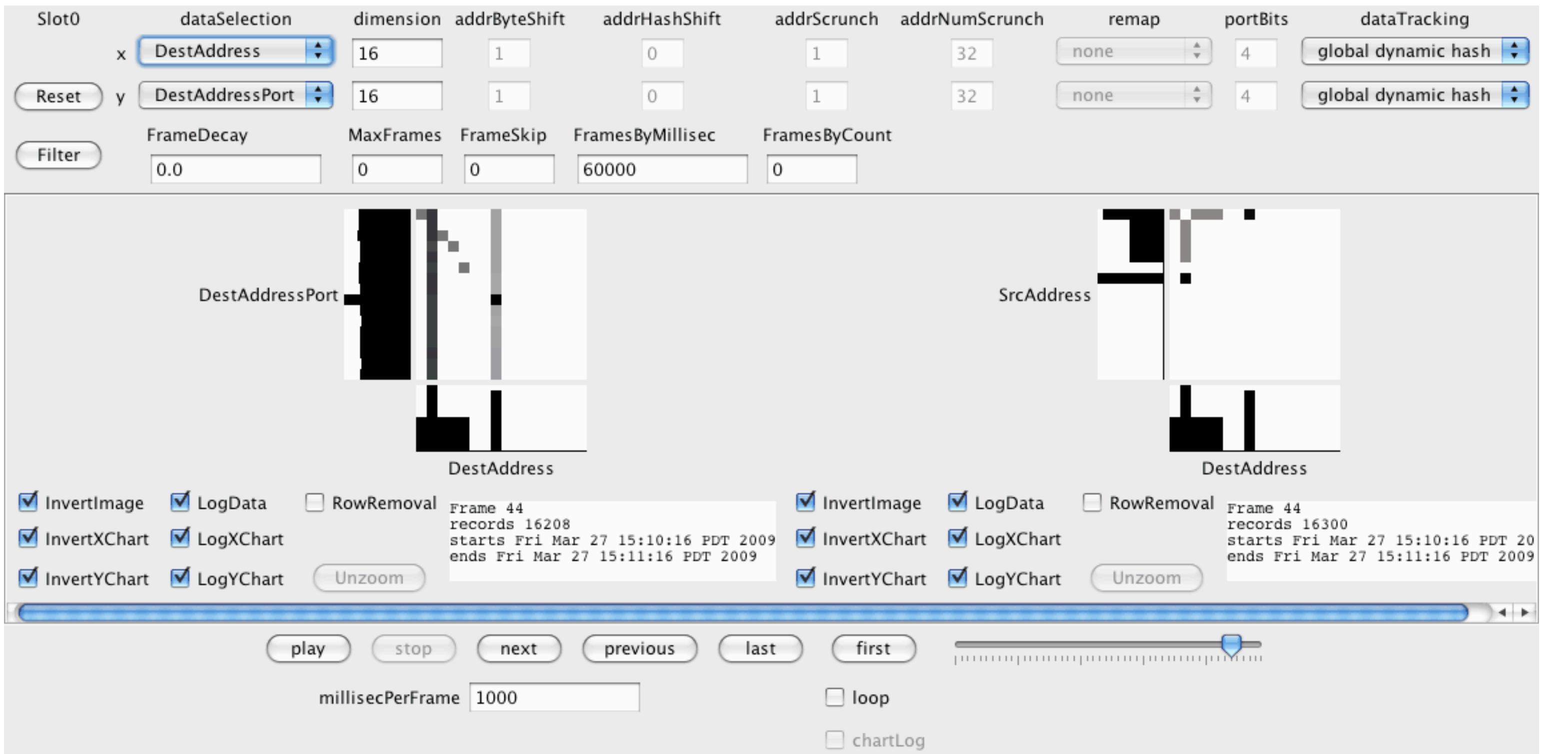
Experiments

- **Learn normal communication patterns**
  - Master/slave relationships
  - Normal and abnormal startup/shutdown
- **Scan the field and control LANs**
- **Rogue Master on the field LAN**

MODBUS (Normal Pattern)



MODBUS (Nessus Scan)



Experimental Results

- **No FP in lab setting**
  - Normal operation
  - Non-malicious faults
  - Learned patterns are reasonable
- **Scans**
  - Detected as both anomalous flow and novel pattern
  - Loud scans sometimes trigger events visible at AW
- **Rogue devices**
  - Detected as both anomalous flows and novel pattern
- **MITM (Future)**

Partnership Between R&D and Industry

- SRI (Overall Lead): Intrusion Detection, Protocol Analysis, Event Aggregation
- Sandia National Laboratories: Architectural Vulnerability Analysis, Attack Scenarios, Red Team
- ArcSight: Security Incident Event Management, Situational Awareness Dashboards
- Invensys: Demonstration System, real-world protocol implementations

DATES Summary

- IDS is a necessary complement to perimeter in PCS
- DATES is developing novel approaches beyond signature detection
- Industry partnerships ensure real world relevance


Backup

Similarity Function

- Generalizes N(Intersection)/ N(Union)
- "Intersection" is the sum of the min probabilities where the patterns intersect
- "Union" is the maximal probability where either pattern is non-zero

$$X = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 & \frac{1}{3} \end{bmatrix}$$

$$Y = \begin{bmatrix} \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & 0 \end{bmatrix}$$

Patterns overlap in the first two entries.

Y is minimum probability.

$\Rightarrow$ Numerator $= \frac{2}{5}$

X is maximal probability in the first, second, and sixth entries.

Y is maximal elsewhere.

$\Rightarrow$ Denominator $= \frac{3}{3} + \frac{3}{5} = \frac{8}{5}$

$$Sim(X,Y) = \frac{2/5}{8/5} = \frac{1}{4}$$

Picking the Winner

- Library patterns "compete" for new pattern
- Winner is most similar as long as similarity is over a set threshold
- Winner is slightly modified to include a little of the new pattern.

Algorithm to pick winner :

Find K s.t.

$$Sim(X, E_K) \geq Sim(X, E_k)\ \forall k$$

$X =$ observed pattern

$E_k =$ kth pattern exemplar in library

If $Sim(X, E_K) \geq T_{match}$, E_K is the winner

Else insert X into the library of pattern exemplars

$T_{match} =$ Minimum match threshold

$$E_K \leftarrow \frac{1}{n_K + 1}\left(n_K E_K + X\right)$$

$n_K =$ Historical (possibly aged) count of observances of E_K

Determining "Rare"

- If large number of patterns is learned, many may be rare
- Alert on tail probability
- Technique does not work for large number of patterns, but tail prob approach does no harm

$\Pr(E_K) =$ Historical probability of pattern K

$$= \frac{n_K}{\sum_k n_k}$$

$Tail\_\Pr(E_K) =$ Historical tail probability of pattern K

$$= \sum_{\Pr(E_k) \geq \Pr(E_j)} \Pr(E_j)$$

$If\ Tail\_\Pr(E_K) \leq T_{alert}$, generate alert

$T_{alert} =$ alert threshold

Protocol Model: Individual fields

- **MODBUS function codes are one byte**
  - 256 possible values, but
  - MSB is used by servers to indicate exception
  - 0 is not valid, so valid range in 1-127
- **Range is partitioned into public, user-defined, and reserved**
  - With no further knowledge, can construct a “weak specification”
- **Many actual devices support a much more limited set of codes**
  - Permits definition of a stronger, more tailored specification

Protocol Model: Dependent Fields

- **Encode acceptable values of a field given the value of another field**
  - Example dependent fields include length, subfunction codes, and arguments
  - For example, “read coils” function implies the length field is 6
  - For other function codes, length varies but a range can be specified
- **Specifications for multiple ADUs: future work**

Detecting Unusual Communication Patterns

- **Specification of network access policies**
  - Comms between CZ and DMZ are restricted to corporate historian client and DMZ historian server
  - Comms between DMZ and PCZ are restricted to PCZ SCADA historian and DMZ historian server
  - SCADA server may communicate with the flow computer and the PLC using MODBUS
  - SCADA server may communicate to SCADA historian
  - SCADA HMI may communicate with SCADA server and engineering station
- **Detection of exceptions is via SNORT rules**
- **More complex networks (more devices) can be accommodated via IP address assignment with appropriate subnet masks**