Identifying Critical Nodes in Large Complex Systems Using Temporal Graph Convolutional Networks

Heng Chuan Tan[1], Zbigniew Kalbarczyk[1,2]
[1] Illinois Advanced Research Science Center at Singapore, Singapore
[2] Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, USA

Background/Problem

- Cyber-physical systems face many vulnerabilities and attack exposures due to high connectivity, heterogeneous networks, and reliance on shared resources.
- Given the scale of these interconnected systems and limited defense resources, it is challenging to determine which assets truly matter to prioritize defenses.
- Security teams rely on Common Vulnerability Scoring System (CVSS) scores to decide which vulnerabilities to address first.
- However, CVSS fails to incorporate contextual factors, such as how the devices are connected and which assets are critical.
- Without this context, CVSS can overlook vulnerabilities that pose disproportionate risks due to their position in the network.

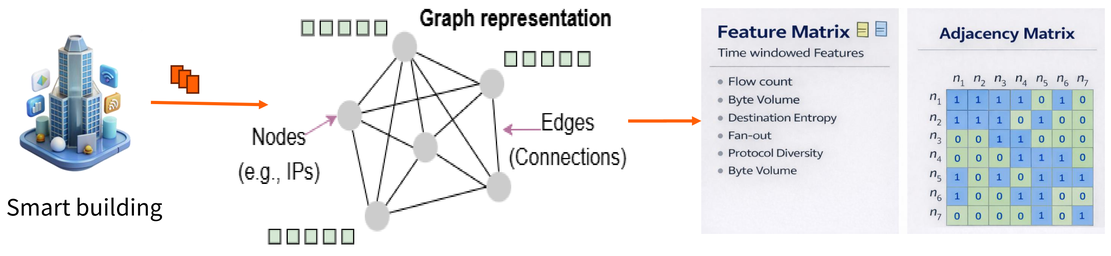
Our Approach

We develop a **Graph Convolutional Network GCN)** that learns network topology and evolving behavior to rank nodes by criticality

1 Model the System as a Graph
- Represent the cyber-physical system as $G = (V, E)$
- **Nodes:** assets (servers, PLCs, IoT, gateways)
- **Edges:** communication relationships
- Captures topology and dependencies between assets

2 Extract Traffic & Temporal Features
- Construct node feature matrix and adjacency matrix from normal traffic
- **Features:** Flow count, byte volume, destination entropy, fan-out ratio, protocol diversity
- Use sliding windows to capture evolving behavior

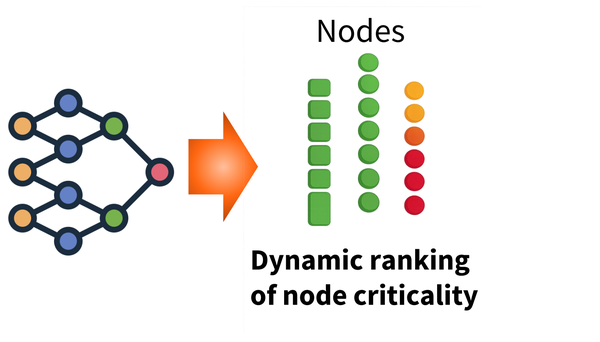
3 Learn Spatio-Temporal Patterns with GCN
- **GCN layers:** Learn structural importance from topology and node features
- **Graph Attention Network (GAT) layers:** Assign different weights to neighbors during feature aggregation.
- **Graph Recurrent Unit (GRU) layers:** Capture temporal evolution of node features and behavior.
- Train with hybrid ranking loss to preserve node ordering.



GCN → Learn network structure from traffic and topology

Graph Attention Network (GAT) → Assign different weights to neighbours

Gated Recurrent Unit (GRU) → Capture temporal patterns in traffic



Dynamic ranking of node criticality

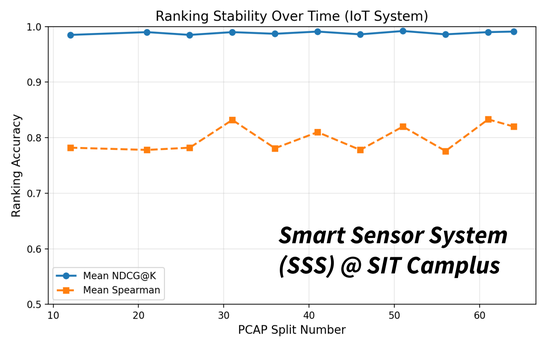
Pinpoints high-risk assets whose compromise causes largest impact

Evaluation

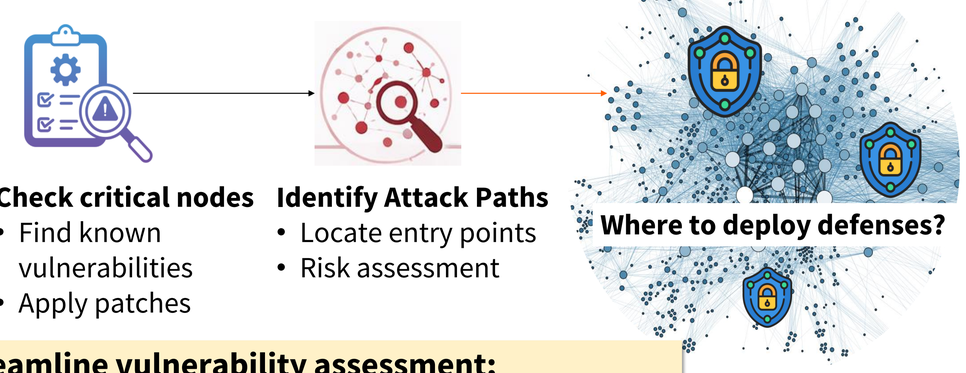
Validated using operational datasets from two real-world systems:
- **SIT Campus @ Punggol Digital District**
  - Building Automation System (BAS)
  - Smart Sensor System (SSS)

Top 10 nodes (SSS) 6 Jun 2025, 12pm to 6:30pm

```
============ Train on capture-20250603.e2mcr1.pcap.split,
============ Test on capture-20250603.e2mcr1.pcap.split11
mean_spearman: 0.7837
mean_mae: 0.0630
mean_ndcg@k: 0.9873
Top 39 critical nodes:
  1: 192.168.2.36          → 0.989343
  2: 192.168.0.23          → 0.337363
  3: 192.168.0.52          → 0.179050
  4: 192.168.0.220         → 0.174647
  5: 192.168.0.157         → 0.174369
  6: 192.168.0.253         → 0.174215
  7: 192.168.0.221         → 0.174139
  8: 192.168.0.243         → 0.173376
  9: 192.168.0.130         → 0.172422
 10: 192.168.0.45          → 0.172223
```



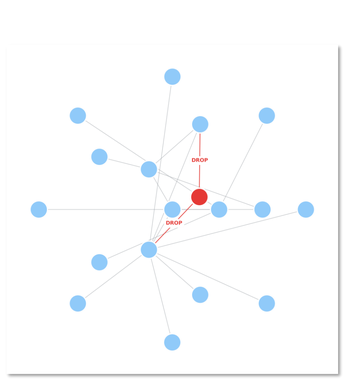
Rank nodes by criticality to prioritize defenses
Stable rankings → Normal operation
Abrupt changes → Topology / configuration updates
Unexplained changes → Possible attack (e.g., scanning, DoS)



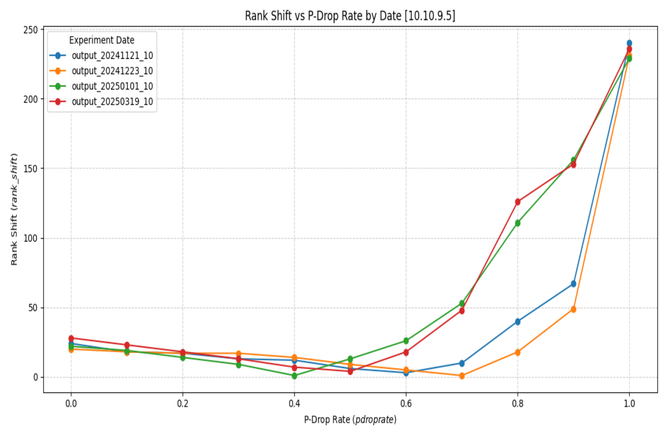
Streamline vulnerability assessment;
Improve situational awareness & guide defense

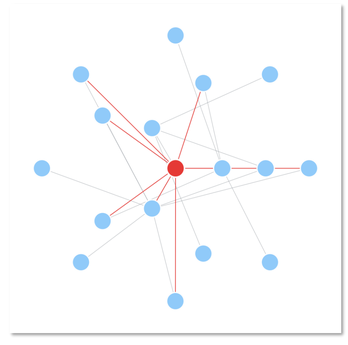
Attack Detection with GCN

- Attacks induce **abnormal rank shifts** in influential nodes
- Targeted disruptions cause **instability in node importance**
- Deviations from baseline indicate **potential compromise**
- 🔍 *Criticality drift = early indicator of cyber attack activity*

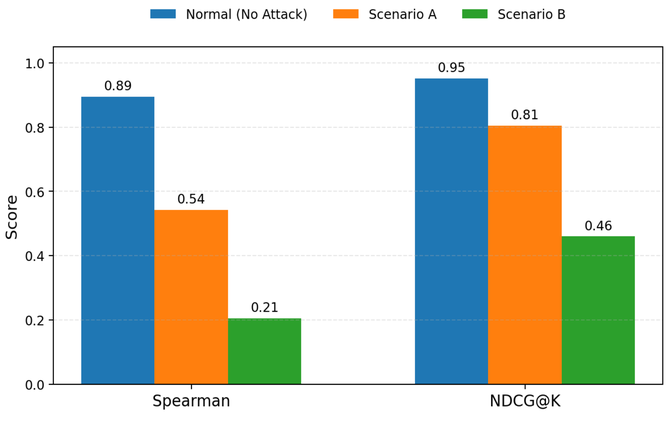


MiTM-Drop





DoS



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