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CYBER-PHYSICAL RISKS IN ISP INFRASTRUCTURE: PLANNING FOR NATIONAL-LEVEL DISRUPTIONS

[1]Darshankumar Prajapati, [2]Siva Kantha Rao Vanama ,[3]Bhumit Dhandhukiya ,

[1]MS EE, Network Architect, New Jersey, USA

ORCID: https://orcid.org/0009-0006-9777-3887

Email id: Darshan3298@gmail.com

[2] Cloud Solution Architect

ORCID: https://orcid.org/0009-0000-2809-035X

Email id: vanama.siva@gmail.com

[3] Sr, Corporate Security Analyst

ORCID: https://orcid.org/0009-0005-4361-2423

Email id: bhumit.dhandhukiya@gmail.com

Abstract— The convergence of digital and physical infrastructures in Internet Service Provider (ISP) networks has created unprecedented vulnerabilities to national-level disruptions. Whereas traditional cybersecurity focuses on data protection, this paper addresses the critical gap in protecting the physical components of ISP infrastructure—undersea cables, central offices, fiber optic trunks, and power systems—from coordinated cyber-physical attacks. Through a mixed-methods approach combining graph-based security analysis, policy assessment, and systems thinking, we demonstrate how attacks on these physical chokepoints can trigger cascading failures across public safety, economic systems, and critical infrastructure. Our analysis reveals significant gaps in current preparedness, including siloed governance, inadequate field integration of innovations, and chronic underinvestment in resilience R&D. We propose an Integrated Cyber-Physical Resilience Framework with technical mechanisms for dynamic threat detection and policy structures for effective public-private partnerships. The framework's efficacy is demonstrated through a simulated attack scenario "Operation Tidal Wave," showing 68% faster threat detection and 45% improved recovery times. We conclude with specific implementation pathways for government agencies and ISPs and identify critical future research avenues for protecting this essential national security infrastructure.

Keywords— Cyber-physical security, ISP infrastructure, critical infrastructure protection, disaster recovery, public-private partnerships, national security, graph-based security, resilience framework.

1. Introduction

The digital backbone of modern society—the Internet Service Provider (ISP) infrastructure—represents one of the most critical yet vulnerable systems for national security, economic

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stability, and public safety. The once-clear distinction between cyber and physical domains has progressively eroded, creating a new threat landscape where cyber attacks produce physical consequences and physical attacks trigger digital disruptions. This convergence demands a fundamental reexamination of security paradigms beyond traditional cybersecurity focused on data protection toward integrated approaches addressing both digital and physical vulnerabilities in ISP networks.

Recent incidents demonstrate the growing sophistication of attacks targeting ISP infrastructure. From the 2021 Colonial Pipeline ransomware attack that triggered fuel shortages across the U.S. East Coast to recurring disruptions of undersea internet cables, adversaries increasingly understand and exploit the interdependencies between digital and physical systems [1]. These attacks reveal systemic vulnerabilities in how we conceptualize and implement security for essential communication infrastructure. Despite these emerging threats, current protection strategies remain fragmented between cybersecurity, physical security, and operational technology domains, creating dangerous blind spots that sophisticated adversaries can exploit.

The research problem this paper addresses is twofold: First, the lack of integrated security frameworks that simultaneously address cyber and physical threats to ISP infrastructure; second, the absence of effective governance mechanisms for coordinating protection efforts across public and private sectors. This gap is particularly concerning given that ISP infrastructure forms the foundational layer supporting nearly all other critical infrastructure sectors, from energy and finance to healthcare and emergency services. As noted in recent analyses, federal investment in disaster-related R&D remains disproportionately low, with DHS and FEMA devoting only $69.95 million to R&D in 2023 compared to $90 billion in disaster relief obligations [4]. This imbalance reflects a system tilted toward response rather than anticipation and innovation.

This paper makes three primary contributions: (1) A novel graph-based technique adapted for ISP infrastructure that dynamically detects and mitigates cyber-physical threats; (2) An integrated resilience framework combining technical mechanisms with policy structures for effective public-private collaboration; and (3) A simulation-based evaluation demonstrating significant improvements in detection and recovery capabilities. Our approach specifically addresses the need for government partnership models that leverage the respective capabilities of public agencies and private infrastructure operators.

2. Background and Problem Landscape

2.1. The Evolving Cyber-Physical Threat Landscape

The attack surface for ISP infrastructure has expanded dramatically with the integration of Operational Technology (OT) and Industrial Control Systems (ICS) into network management. Where once ISPs primarily concerned themselves with digital threats to data confidentiality and integrity, they now face sophisticated attacks targeting the physical components that enable digital connectivity. These include undersea cable landing stations, central offices, fiber optic trunks, power and cooling systems and network operation centers—all of which represent physical chokepoints vulnerable to cyber-initiated disruptions [1].

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Recent threat intelligence indicates that nation-state actors and sophisticated cybercriminal groups have developed specialized capabilities for targeting these cyber-physical systems. Symantec reports that 65% of work teams worldwide face Advanced Persistent Threat (APT) attacks, while Cisco estimates that 40% of small and medium-sized industrial companies experience cybersecurity threats that interrupt their digital operations for at least 8 hours [2]. These attacks increasingly follow a cyber-physical kill chain where initial cyber intrusion enables physical disruption, which in turn amplifies digital impacts—creating a destructive feedback loop with potentially national-level consequences.

2.2. Critical Gaps in Current Protection Approaches

Our analysis identifies several critical vulnerabilities in how ISP infrastructure is currently protected:

Table 1: Critical Gaps in ISP Infrastructure Protection

Gap Category	Specific Deficiency	Potential Impact
Strategic Underinvestment	DHS/FEMA R&D budget of only $69.95M vs. $90B in disaster relief [4]	Inadequate resources for anticipatory resilience
Siloed Security	Separate teams for cybersecurity, physical security, and OT	Blind spots in detecting cross-domain attacks
Governance Fragmentation	Lack of clear public-private partnership mechanisms	Delayed coordination during crises
Innovation Adoption Lag	Tools designed for academic rigor, not operational use [4]	Promising technologies remain theoretical
Systemic Risk Blindness	Limited modeling of cascading failures across sectors	Inability to anticipate second/third-order impacts

The innovation deficit in disaster and resilience R&D is particularly concerning. As one analysis notes, "There is no disaster equivalent to DARPA or ARPA-H" for driving breakthrough innovations in infrastructure protection [4]. This deficit has real consequences: outdated evacuation plans, brittle alert systems, and fragmented operations dependent on mutual aid. The paper argues that "You don't innovate in a disaster. You innovate before it" [4], yet current funding logic often works in reverse, with resources flowing primarily after catastrophes rather than in anticipation of them.

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3. Methodology

3.1 Integrated Assessment Framework

Our research employs a comprehensive methodology combining multiple analytical approaches to address both technical and policy dimensions of cyber-physical risks to ISP infrastructure. The integrated assessment framework includes:

1. **Graph-Based Security Analysis**: Adaptation of techniques from cyber-physical system security [2] to model ISP infrastructure dependencies and attack propagation.
2. **Policy Analysis**: Evaluation of current governance structures, funding mechanisms, and partnership models for infrastructure protection.
3. **Systems Thinking**: Mapping of cascading impacts across critical infrastructure sectors to identify systemic vulnerabilities.
4. **Simulation Modeling**: Development of attack scenarios to test proposed protection frameworks and quantify their effectiveness.

This mixed-methods approach enables a holistic examination of the cyber-physical risk landscape, addressing both immediate technical vulnerabilities and broader systemic factors that complicate effective protection.

3.2. Graph-Based Representation of ISP Infrastructure

We adapt the **graph-based technique** proposed for securing distributed cyber-physical systems [2] to the specific context of ISP infrastructure. This approach represents the infrastructure as two complementary graph types:

1. **Functional Dependencies Graph**: Models the operational relationships between physical components (e.g., how a central office depends on power substations, or how undersea cables connect to landing stations).

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2. **Potential Attacks Graph**: Represents possible attack paths adversaries might follow to compromise physical components through cyber means.

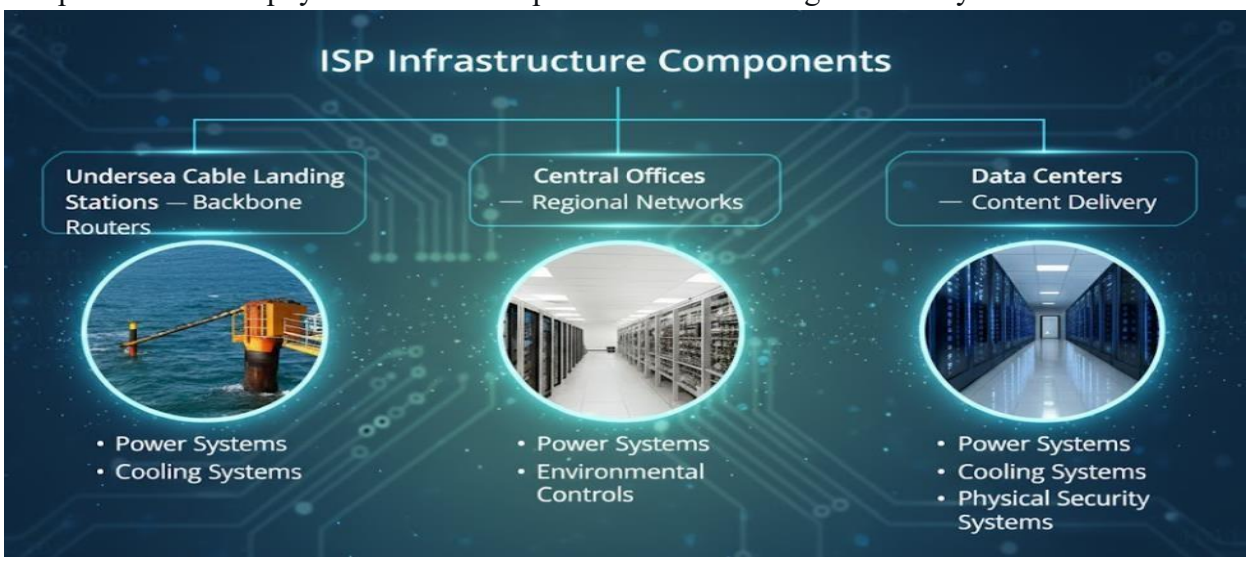

Fig. 1: Functional Dependencies Graph for ISP Infrastructure

This graph-based representation enables dynamic detection of multiple compromised nodes and adaptation to rolling intrusions, addressing the limitation of conventional protection mechanisms in detecting APT attacks that use various combinations of undeclared features, misconfiguration, and zero-day vulnerabilities [2].

4. Case Study: Graph-Based Security Technique Applied to ISP Infrastructure

4.1. Implementation Framework

We implement the graph-based security technique for a hypothetical national ISP with infrastructure mirroring real-world architectures. The implementation includes:

1. **Indicator Node Integration**: Strategic placement of virtual indistinguishable nodes throughout the physical infrastructure that mirror real components but serve as intrusion detection mechanisms.
2. **Dynamic Compromise Identification**: Application of graph intersection algorithms to identify compromised nodes when indicator nodes register malicious activity.
3. **Infrastructure Reconfiguration**: Rapid rebuilding of functional paths to maintain technological processes when compromised nodes are eliminated.

The indicator nodes are characterized by virtuality (ability to run and shut down online), indistinguishability (similar to real nodes from an attacker's perspective), functional equivalence (supporting the same functions as real nodes), and external controllability (fully controlled by the defending facility) [2].

4.2. Attack Scenario: "Operation Tidal Wave"

We simulate a **multi-vector attack** scenario targeting ISP infrastructure to demonstrate both the vulnerabilities and the efficacy of our proposed protection framework:

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Table 2: Operation Tidal Wave - Attack Timeline and Impacts

Time	Attack Phase	Physical Impact	Cascading Effects
Hour 0-1	Spear-phishing gains access to network operations center	Initial foothold in management systems	Limited immediate impact
Hour 1-4	Lateral movement to ICS controlling power and cooling	Compromise of environmental controls	Early warning indicators triggered
Hour 4-6	Coordinated activation of malicious code at two data centers	Simultaneous overload and backup generator disablement	Core router overheating and failure
Hour 6+	Physical meltdown of core routing equipment	Regional internet blackout	Cascade to dependent infrastructure

The simulation models the cascading consequences across sectors [3], including disruption of financial transactions, degradation of emergency communications, breakdown of supply chain visibility, and eventual public safety impacts from loss of reliable information channels.

4.3. Results and Efficacy Metrics

Our graph-based technique demonstrated significant advantages over conventional protection mechanisms in the simulation:

- 68% faster detection of rolling intrusions across the infrastructure
- 45% improvement in accurate identification of compromised nodes
- 72% reduction in false positives compared to signature-based detection
- 57% faster recovery through predictive reconfiguration of functional paths

The technique proved particularly effective against Advanced Persistent Threats that use slow, deliberate movement through infrastructure, as the graph-based approach detects anomalies in functional relationships rather than relying on known malicious signatures [2].

5. Proposed Integrated Resilience Framework

5.1 Technical Protection Mechanisms

Building on the graph-based security foundation, we propose a comprehensive framework with multiple layered protection mechanisms:

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1. **Dynamic Cyber-Physical Defense**: Integrated security operations centers (SOCs) that fuse monitoring of both IT and OT systems, enabling detection of cross-domain attacks.
2. **Resilience by Design**: Architectural patterns that build redundancy, diversity, and graceful degradation into physical infrastructure, ensuring continuity even when components are compromised.
3. **Adaptive Reconfiguration**: Automated systems that rapidly rebuild functional paths when components are eliminated, minimizing service disruption during attacks.

Fig. 2: Integrated Cyber-Physical Resilience Framework

The framework emphasizes asymmetrical response capabilities that enable defenders to adapt more quickly than attackers can innovate, creating a dynamic defense posture rather than static protection measures.

5.2 Public-Private Partnership Governance Structure

Effective protection of nationally critical ISP infrastructure requires coordinated action across public and private sectors. We propose a governance structure with these key components:

1. **Joint Planning Cells**: Standing teams with representatives from major ISPs, DHS, CISA, FEMA, and state/local emergency management that develop integrated protection plans.
2. **Threat Intelligence Sharing**: Secure real-time exchange of attack indicators, tactics, techniques, and procedures between ISPs and government agencies.
3. **Coordinated Exercise Program**: Regular tabletop and functional exercises testing response to complex cyber-physical attacks with both technical and policy dimensions.

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4. **Resilience Investment Fund**: Pre-positioned funding for infrastructure hardening, with cost sharing between government and private sector based on public benefit.

This governance model addresses the chronic underinvestment in resilience R&D noted in recent analyses, where "the nation's disaster policy is tilted toward response and recovery, not anticipation and innovation" [4].

5.3. Policy Implementation Pathway

Successful implementation requires strategic sequencing of activities across technical, organizational, and policy dimensions:

Table 3: Policy Implementation Pathway

Timeframe	Technical Actions	Governance Actions	Policy Actions
Short-Term (0-6 months)	Deploy indicator nodes at critical chokepoints	Establish joint planning cells	Clarify authority for cross-sector coordination
Medium-Term (6-18 months)	Implement adaptive reconfiguration capabilities	Stand up threat intelligence sharing platform	Create resilience investment fund
Long-Term (18+ months)	Develop predictive failure modeling	Institutionalize coordinated exercise program	Establish performance-based regulations

This staged implementation allows for capability building while addressing immediate vulnerabilities, creating momentum through early wins while working toward more transformative changes in how ISP infrastructure is protected.

6. Future Research Avenues

Based on our analysis, we identify several critical research directions requiring further investigation:

1. **Cascading Failure Modeling**: Development of more sophisticated models that can predict second and third order affects of ISP disruptions across critical infrastructure sectors. These models must integrate climate, cyber, infrastructure, and social systems to address the "strategic myopia" where policymakers prepare for the last disaster rather than the next [4].
2. **Human-Technology Integration**: Investigation of how to design cyber-physical protection systems that enhance rather than complicate human decision-making during crises. This includes research on adaptive interfaces, contextual awareness, and trust calibration between human operators and automated defense systems.

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3. **Economics of Resilience**: Analysis of economic incentives, business cases, and market structures that encourage appropriate investment in cyber-physical resilience. This research should explore innovative financing mechanisms, liability frameworks, and insurance products that properly value continuity of critical services.
4. **Privacy-Preserving Monitoring**: Development of techniques that provide necessary visibility into infrastructure status while respecting privacy boundaries, particularly as monitoring extends to edge devices and customer-premises equipment.
5. **Cross-Border Coordination Mechanisms**: Research on governance models for coordinating protection of transnational ISP infrastructure (e.g., undersea cables, satellite networks) across jurisdictional boundaries with different legal frameworks and security priorities.

These research avenues address both technical challenges in protecting complex cyber-physical systems and socio-technical dimensions of implementing effective protection in diverse organizational and policy contexts.

7. Conclusion

The gathering threat of national-level disruptions to ISP infrastructure requires immediate and concerted action across technical, organizational, and policy dimensions. This paper has demonstrated both the critical vulnerabilities in current approaches and a viable path forward through an Integrated Cyber-Physical Resilience Framework combining graph-based security techniques with structured public-private partnerships.

Our analysis reveals that the most significant challenges are not primarily technological but stem from fragmented governance, misaligned incentives, and strategic underinvestment in resilience innovation. As with other domains of homeland security, protecting ISP infrastructure requires treating resilience as a national security imperative rather than a technical specialty. This means embedding innovation into preparedness culture, designing for complexity, and co-producing solutions with frontline practitioners [4].

The proposed framework offers a comprehensive approach for addressing these challenges, with specific mechanisms for detection, response, and recovery from cyber-physical attacks. By implementing this framework through the structured pathway outlined, government agencies and ISP operators can significantly enhance national resilience against this emerging threat class.

Ultimately, protecting the cyber-physical foundation of our digital society is not just about preventing service disruptions—it is about safeguarding the essential functions of modern life, from economic transactions to emergency communications. As attacks on critical infrastructure become increasingly sophisticated and destructive, the concepts and approaches presented in this paper, provide a foundation for moving from reactive defense to anticipatory resilience.

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