Multilevel Structural Diversity
using Multipath Communication for Future Internet Resilience and Survivability

James P.G. Sterbenz*†
Джеймс Ф.Г. Штербэнз 제임스 스터벤츠 司徒傑莫
Abdul Jabbar, Justin Rohrer, Egemen Çetinkaya,
Dongsheng Zhang 张东升, Yufei Cheng 成宇飞, Anh Nguyễn

*Department of Electrical Engineering & Computer Science
Information Technology & Telecommunications Research Center
The University of Kansas
†School of Computing and Communications, Infolab 21
Lancaster University

jpgs@ittc.ku.edu
http://www.ittc.ku.edu/~jpgs
http://wiki.ittc.ku.edu/resilinets

Where is Kansas?
Geography Lesson

Multilevel Structural Diversity
Outline

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

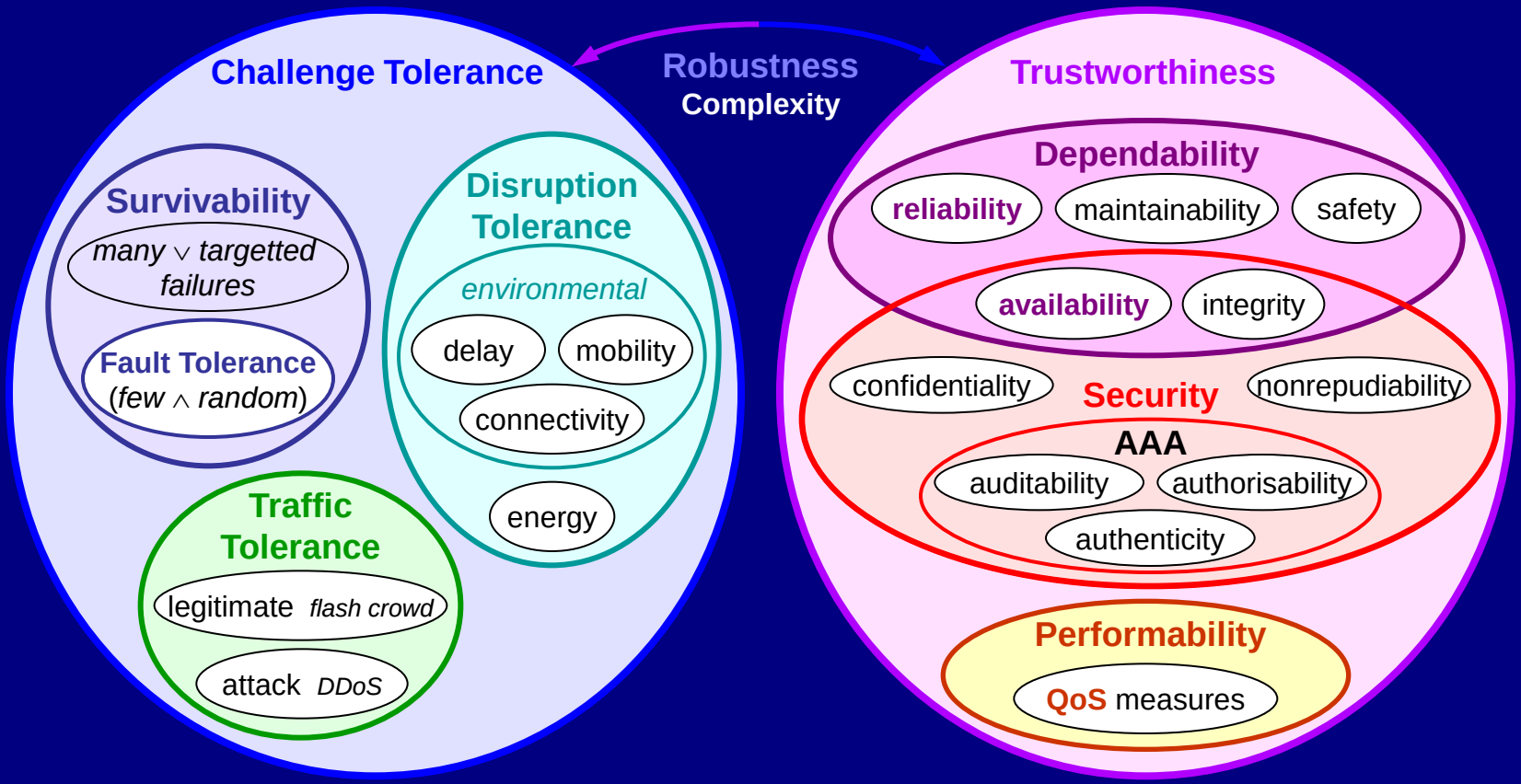
Resilience and Survivability
Motivation and Definition

- Increasing reliance on network infrastructure
  - ⇒ Increasingly severe consequences of disruption
  - ⇒ Increasing attractiveness as target from bad guys
- Need *resilience*
  - provide and maintain acceptable service
  - in the face of faults and challenges to normal operation
- Challenges
  - …
  - large scale disasters (natural and human-caused)
  - malicious attacks from intelligent adversaries

ResiliNets Initiative
Goals

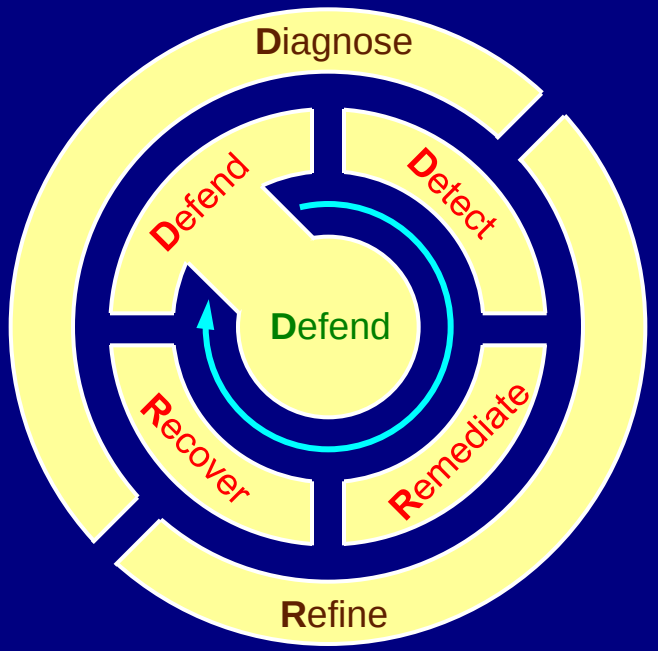
- Understand network structure and vulnerabilities
  - develop new models and tools for analysis
- Develop ways to increase network resilience
  - improving existing networks under cost constraints
  - increase cost to attackers
  - Future Internet design
  - validate by simulation and experimentation
- Funded primarily by
  - US NSF FIND and GENI programs and open call (with Medhi)
  - US DoD
  - EU FP6 FIRE programme (with David Hutchison)

Scope of Resilience
Relationship to Other Disciplines



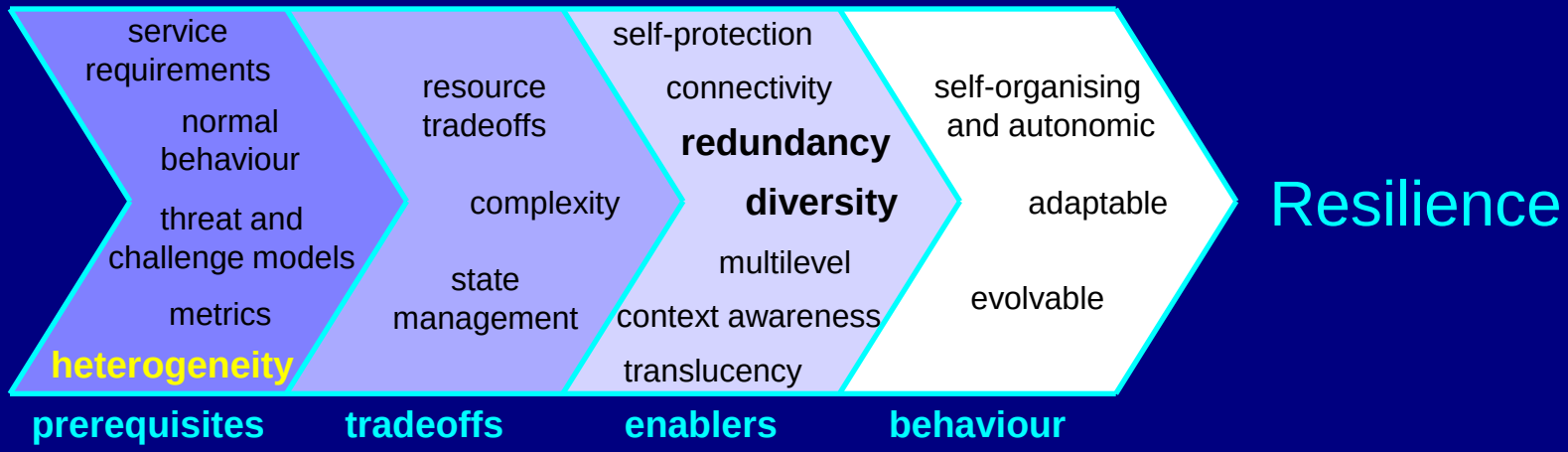
ResiliNets Strategy
D^2R^2 + DR

- Two phase strategy for resilience
- Real time control loop: D^2R^2
  - defend
    - passive
    - active
  - detect
  - remediate
  - recover
- Background loop: DR
  - diagnose
  - refine



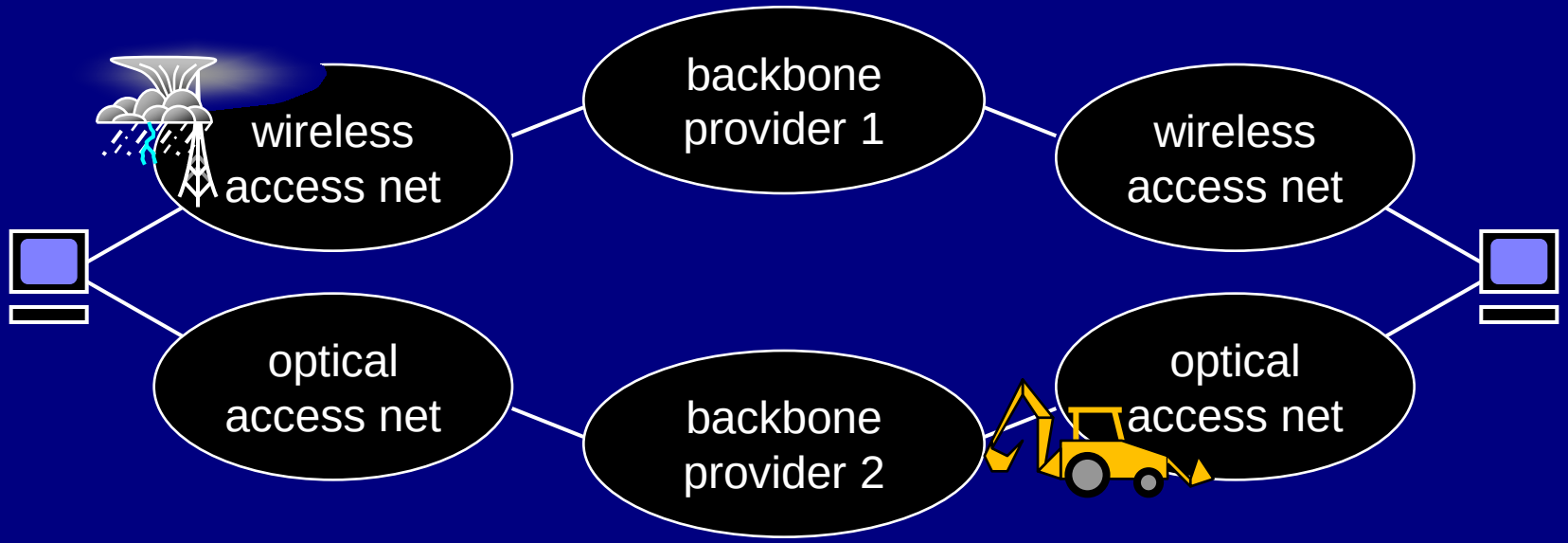
[Wiki 2005, *ComNet* 2010]

ResiliNets Principles
High Level Grouping



- Prerequisites: to understand and define resilience
- Tradeoffs: recognise and organise complexity
- Enablers: architecture and mechanisms for resilience
- Behaviour: require significant complexity to operate

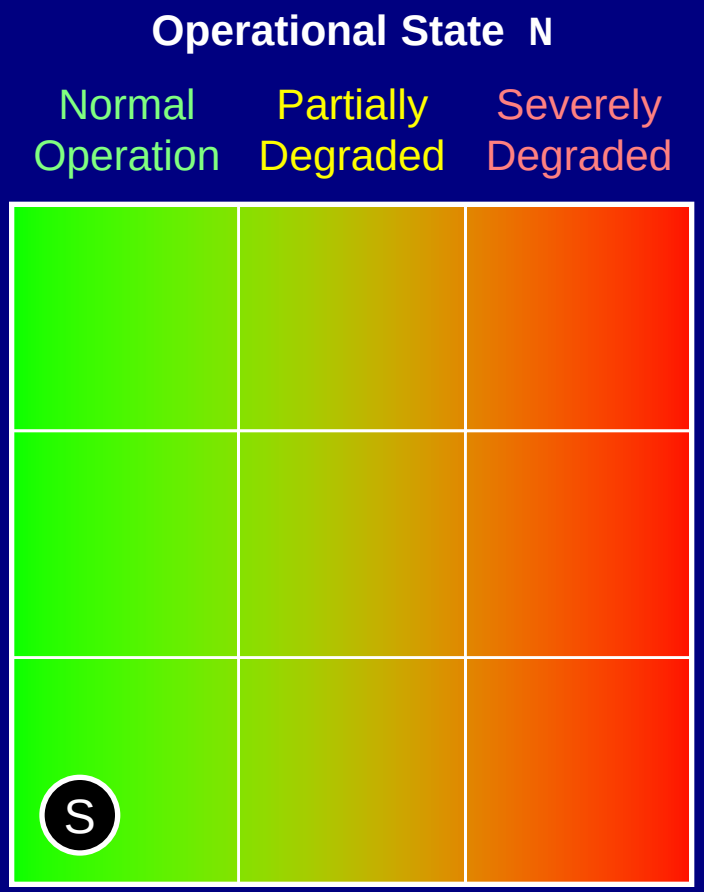
Resilience Principles
Redundancy, Diversity, Heterogeneity



- Diversity
  - mechanism (wired & wireless), provider, *geographic path*
- Multipath transport
  - spreading (erasure code) or as hot-standby

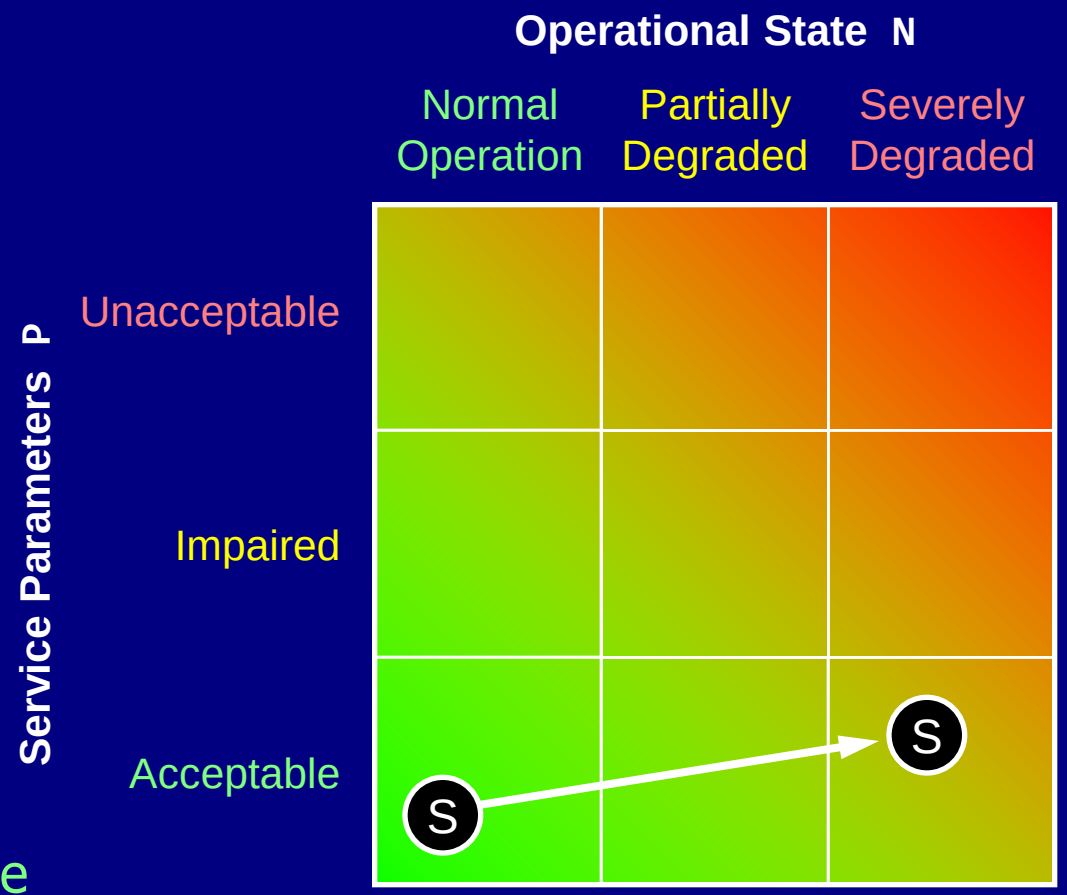
ResiliNets State Space
Operational Resilience

- Operational resilience
  - minimal degradation
  - in the face of challenges
  - objective function of operational metrics
- Resilience state
  - remains in normal operation



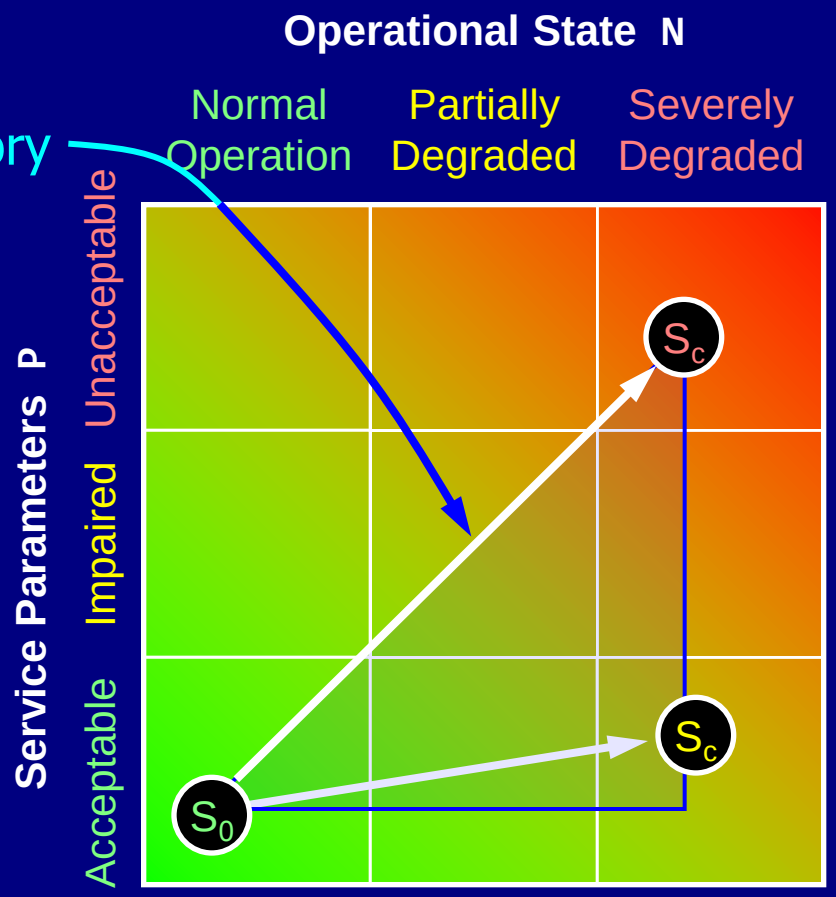
ResiliNets State Space
Service Resilience

- Service resilience
  - acceptable service
  - in the face of degraded operation
  - obj. func. of service metrics
- Resilience state
  - remains in acceptable service

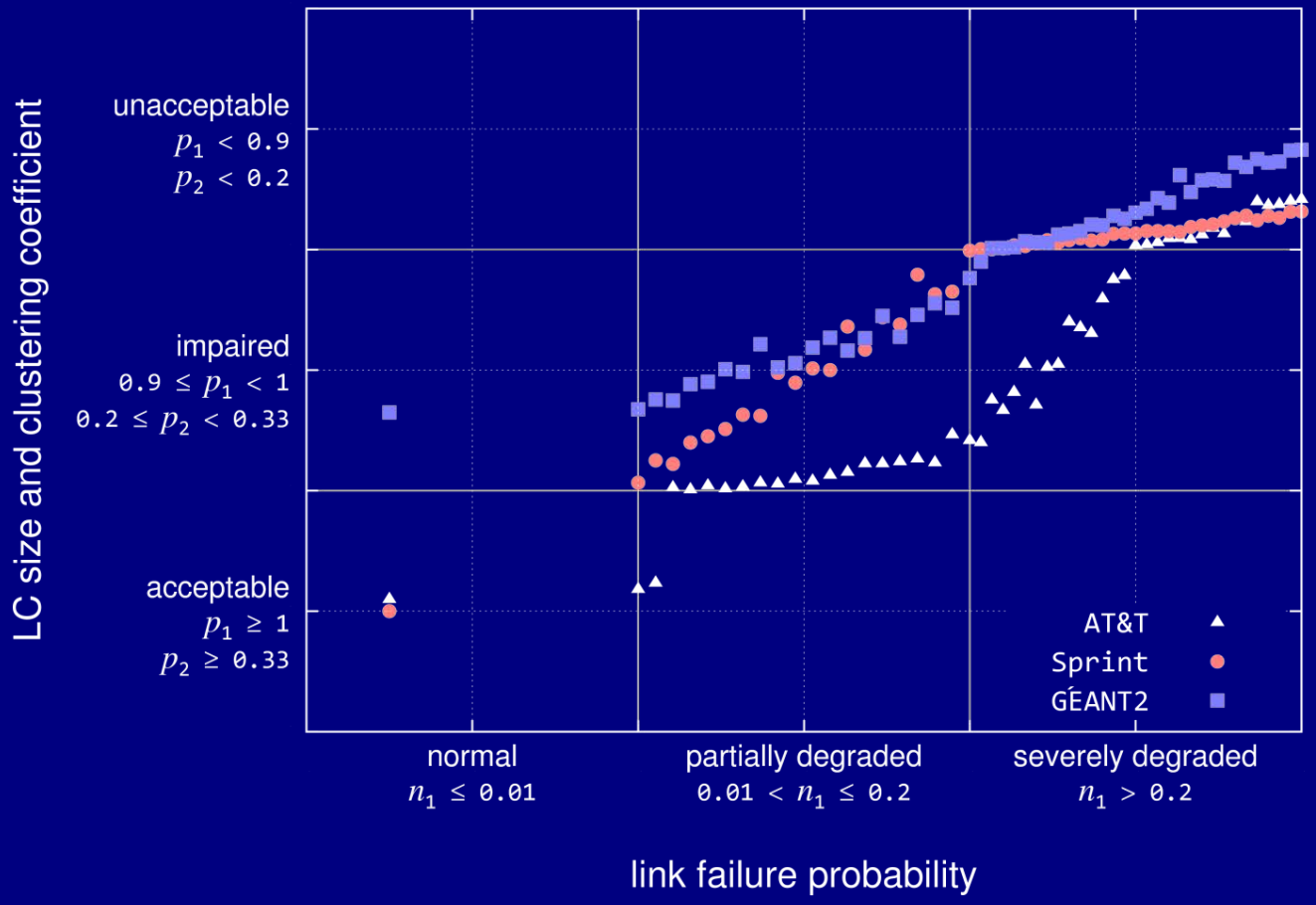


ResiliNets State Space
Quantification of Resilience

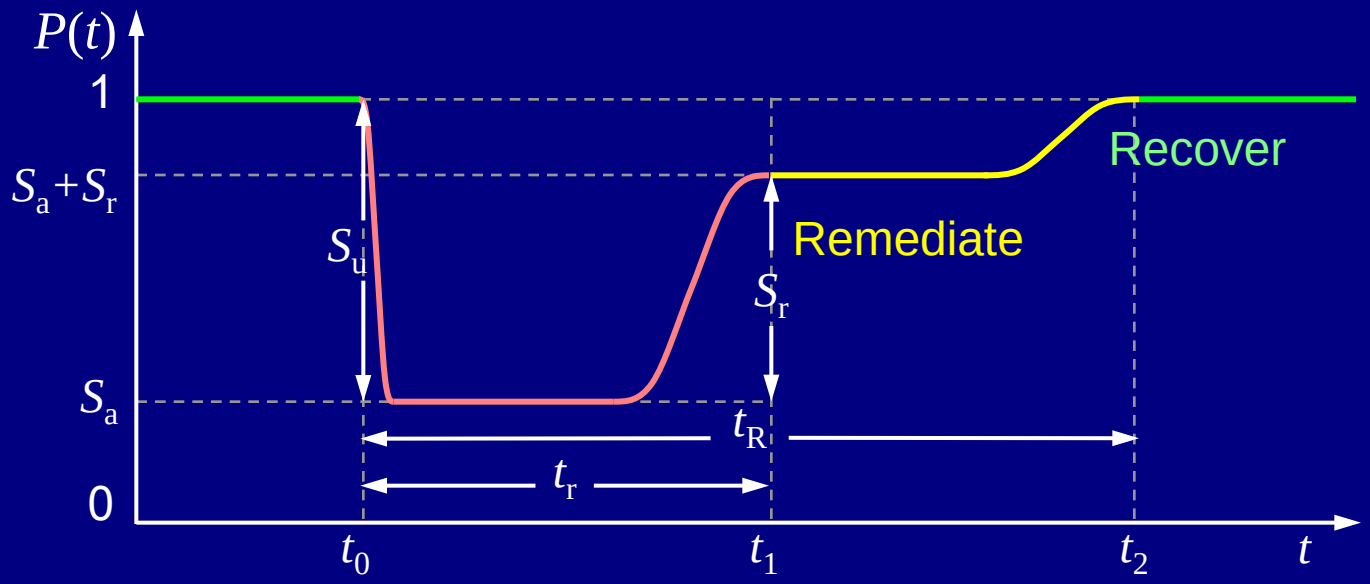
- Resilience
  - $\mathbb{R}$ = 1– area under trajectory
  - for particular scenario
  - resilience $\Re$ over all scenarios
- Types of analysis
  - static [Jabbar 2010]
  - temporal
  - reflective



ResiliNets State Space
Network Topology Analysis Example



ResiliNets State Space
Temporal Analysis

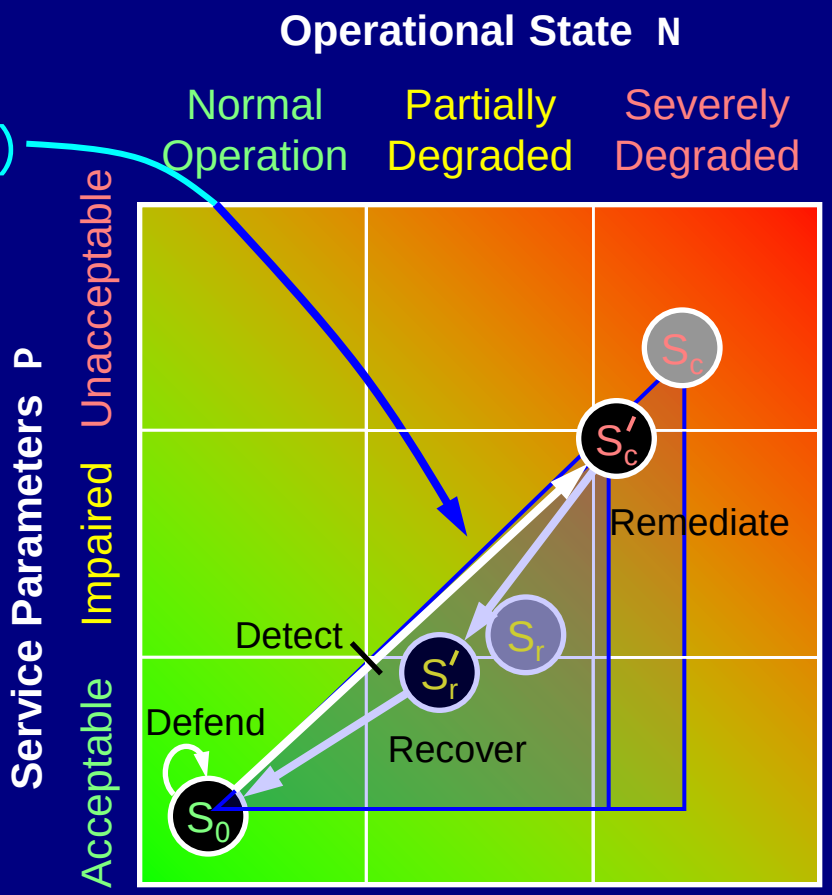


- Temporal resilience weight area by t_r and t_R
- After refinement resilience increased $\mathbb{R}' > \mathbb{R}$ iff
  - $t_r' \leqslant t_r$ and
  - $t_R' \leqslant t_R$

ResiliNets State Space

D^2R^2 + DR State Space Analysis

- Resilience
  - $1-\mathbb{R}$ (area under trajectory)
  - for particular scenario
  - resilience $\Re$ over all scenarios
  - static
    [Jabbar 2010]
  - temporal weighting
    TBD
- Work factor
  - increase cost of attacker
  - for given damage



Multilevel Structural Diversity
Outline

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

Challenge Taxonomy
Overview

- Classification and taxonomy of *challenges*
  - based on fault taxonomy
    - [ALRL 2004] and IFIP 10.4 related publications
- Elementary challenge classes
  - elementary orthogonal classification within fault groups

[DRCN 2013]

Challenge Taxonomy
Abbreviated Correlation Matrix

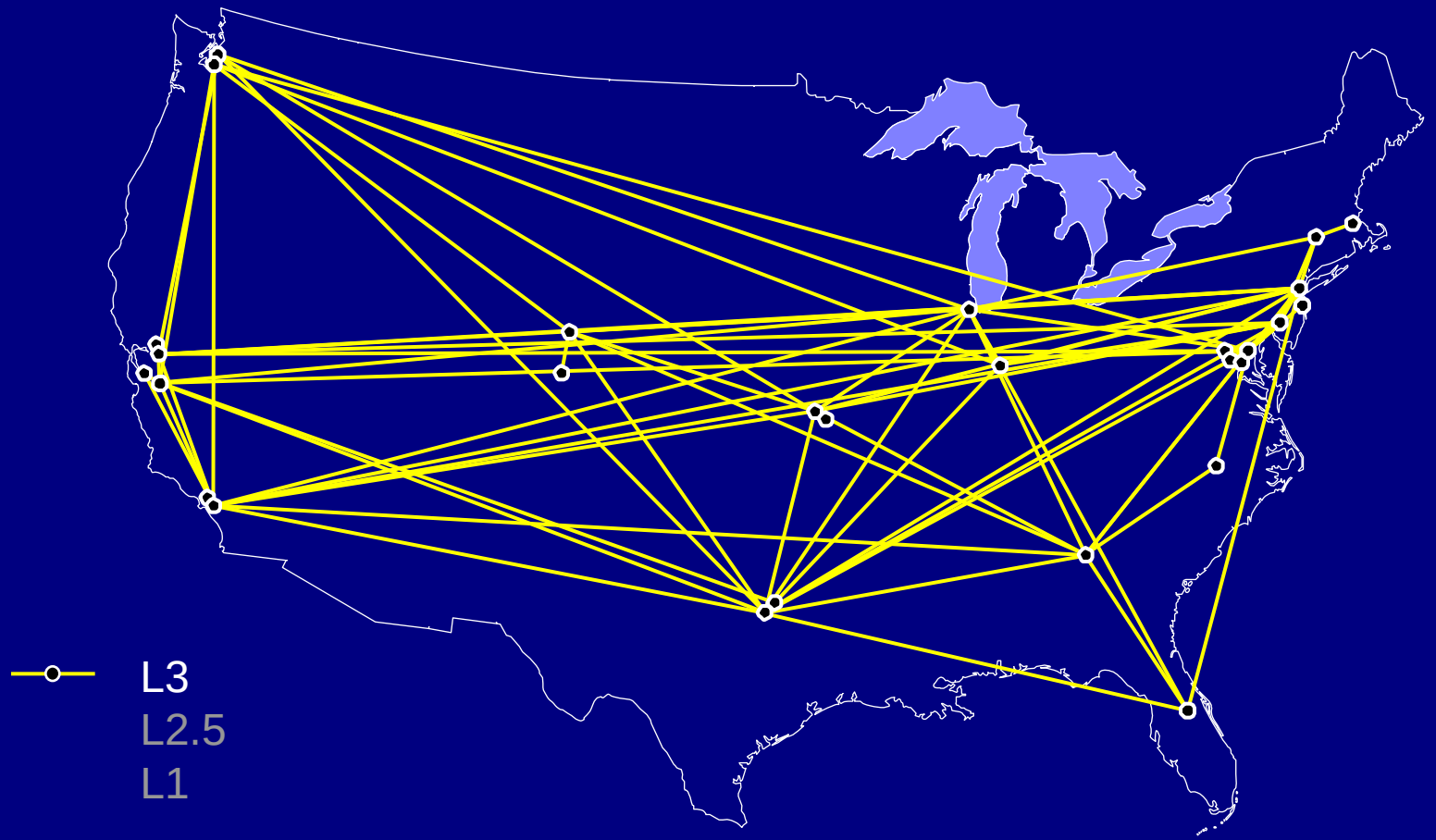
Challenge examples	intent		scope			domain	
	non-malicious	**malicious**	**nodes**	**links**	**area**	**wired**	**wireless**
natural component failures	×		×	×		×	×
misconfiguration	×		×	×	×	×	×
cable cuts	×	×		×		×	
jammers		×	×	×			×
interference	×			×			×
weather precipitation	×			×	×		×
attacks against critical inf.		×	×	×		×	×
natural disasters	×				×	×	×
pandemic	×	×			×	×	×
nationwide Internet outage	×	×			×	×	×
power failure	×				×	×	×
EMP weapon		×			×	×	×
coronal mass ejection	×				×	×	×

Multilevel Structural Diversity
Multilevel Interrealm Resilience

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

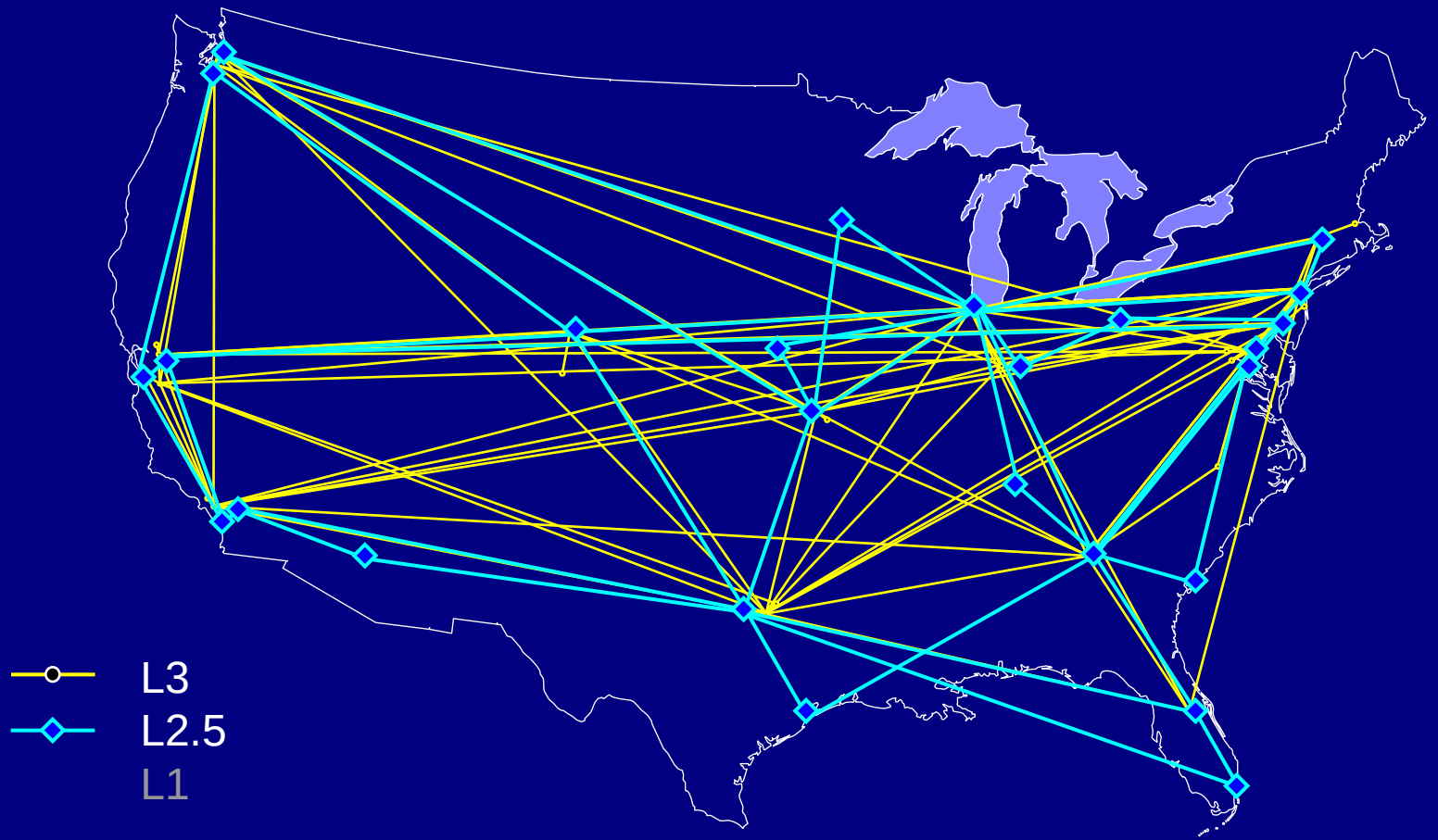
Multilevel Network Topology

Example: Sprint L3 IP PoP Topology



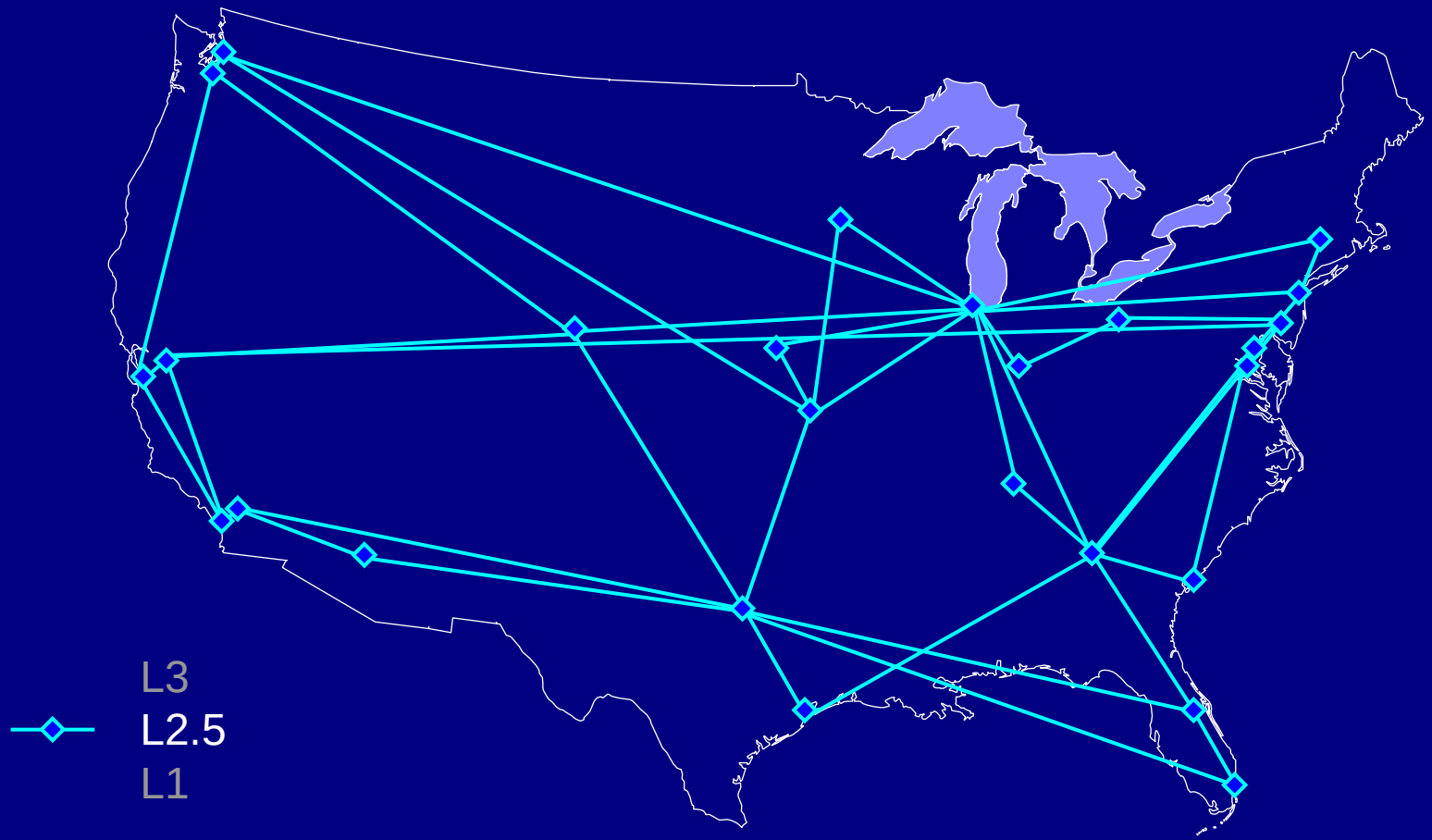
Multilevel Network Topology

Example: Sprint L3 overlay on L2.5



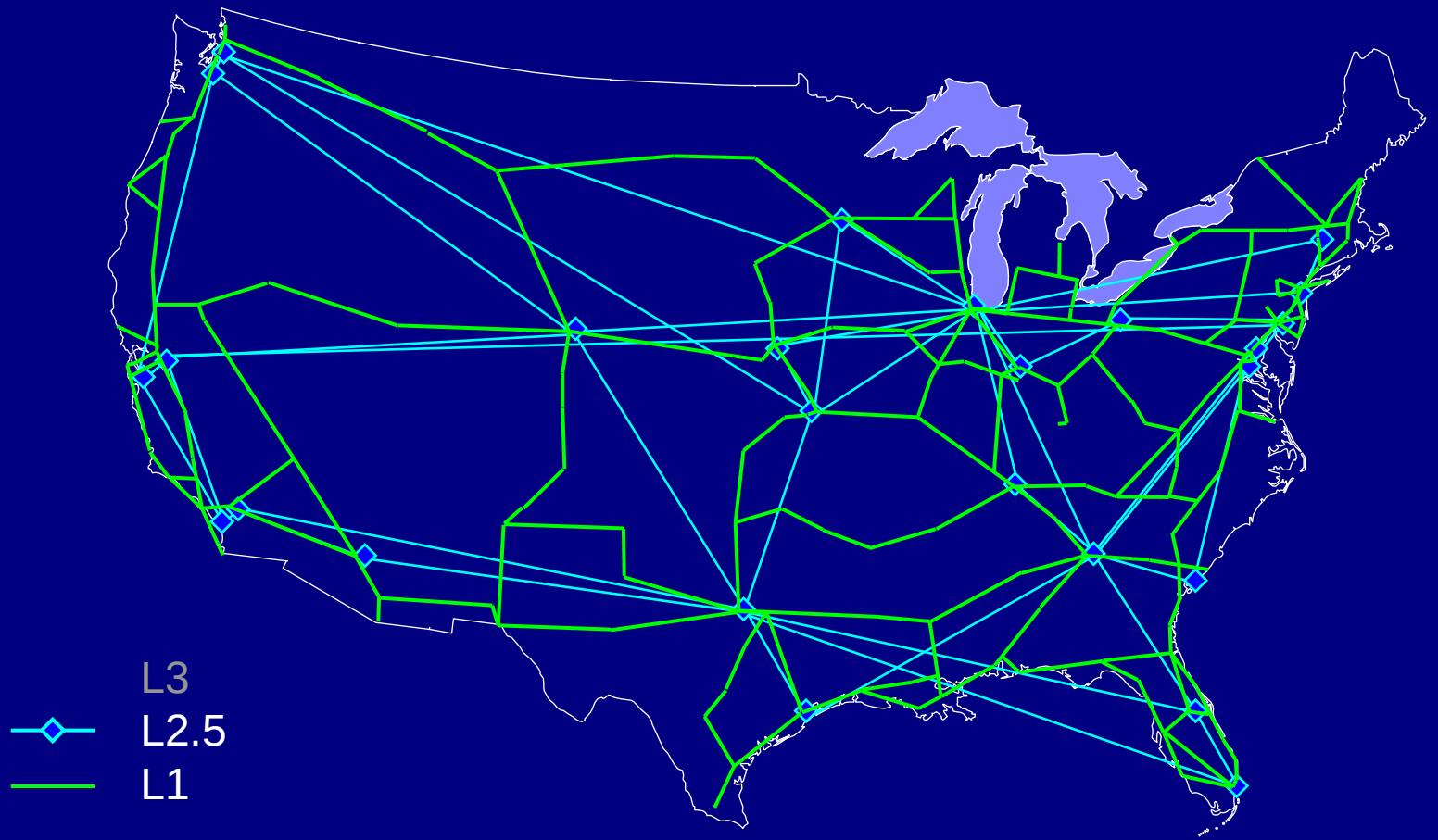
Multilevel Network Topology

Example: Sprint L2.5 MPLS PoP Topology



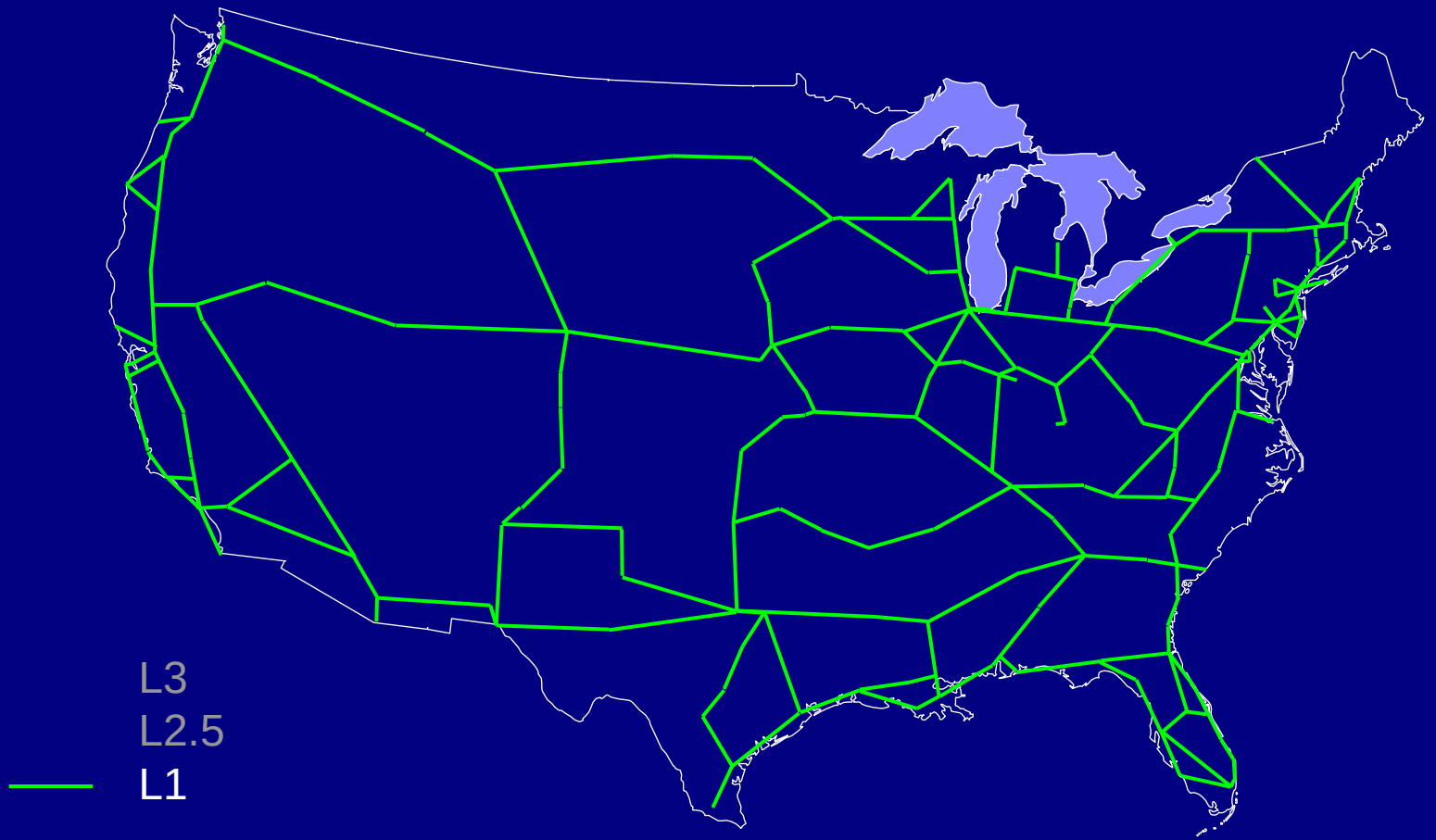
Multilevel Network Topology

Example: Sprint L2.5 overlay on L2/1



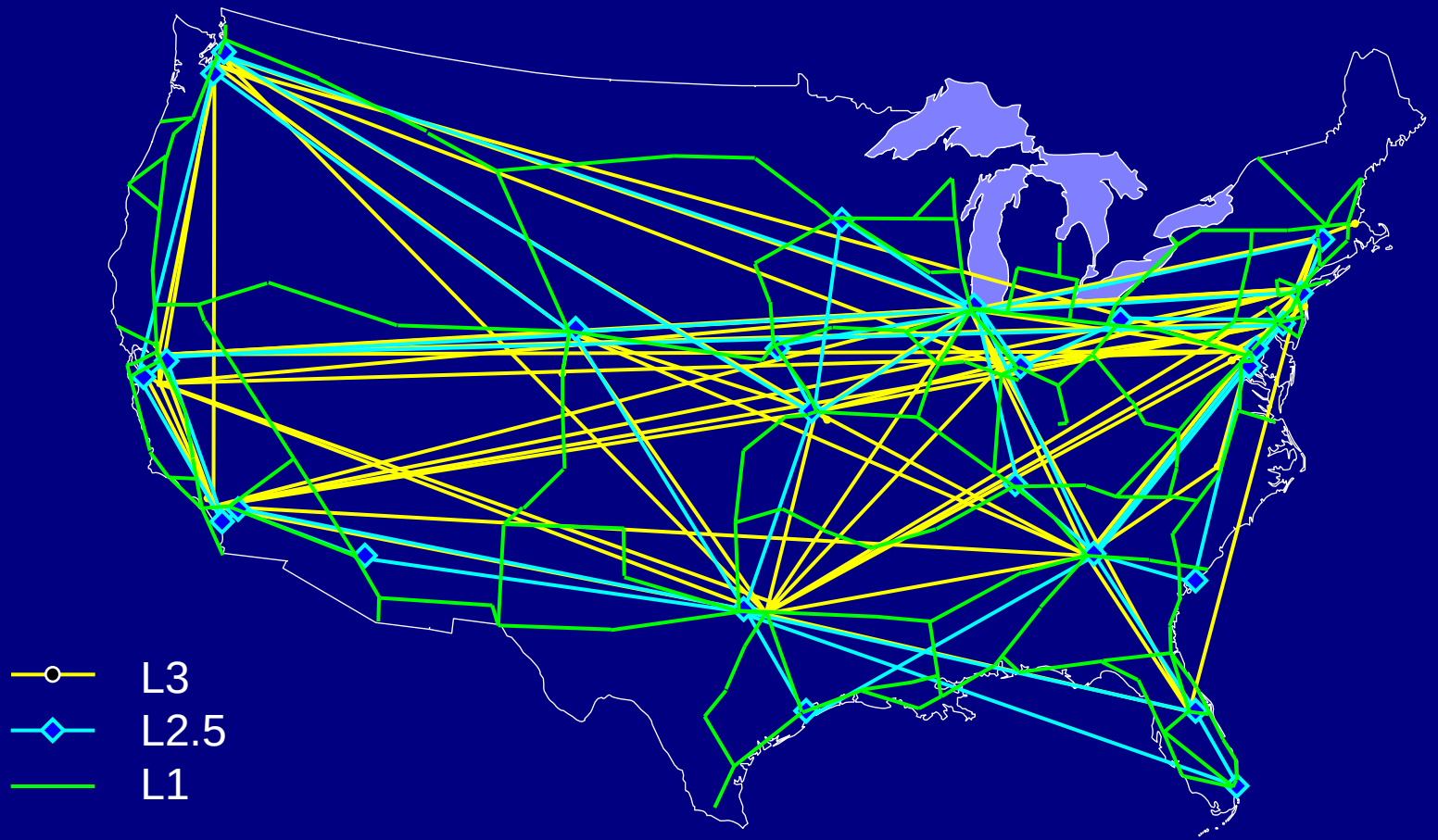
Multilevel Network Topology

Example: Sprint L1 Physical Fiber Topology



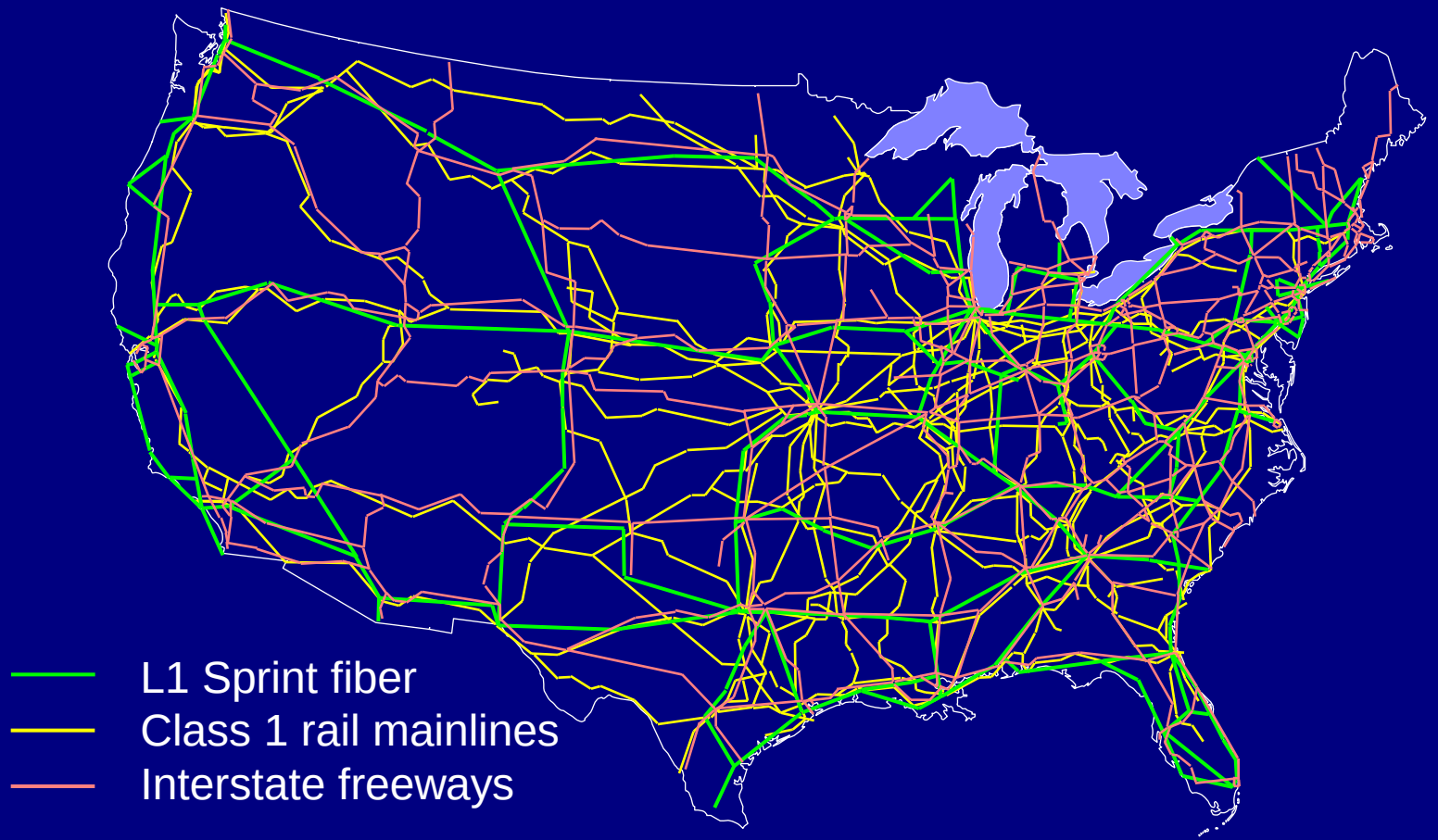
Multilevel Network Topology

Example: Sprint L1–3 Topology



Complex Network Topology

Fiber Relation to Potential Paths



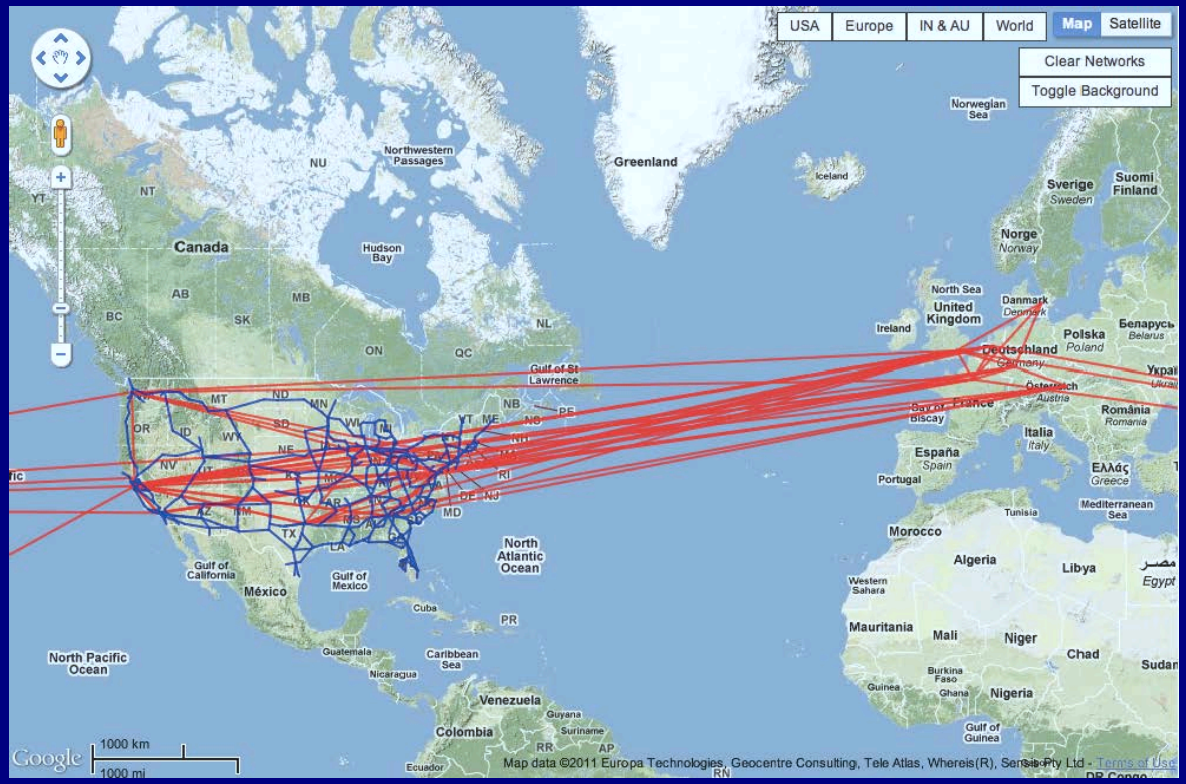
Complex Network Topology
KU-TopView Topology Viewer

L1 Sprint fiber

visualisation ⇔ adjacency matrices

Complex Network Topology

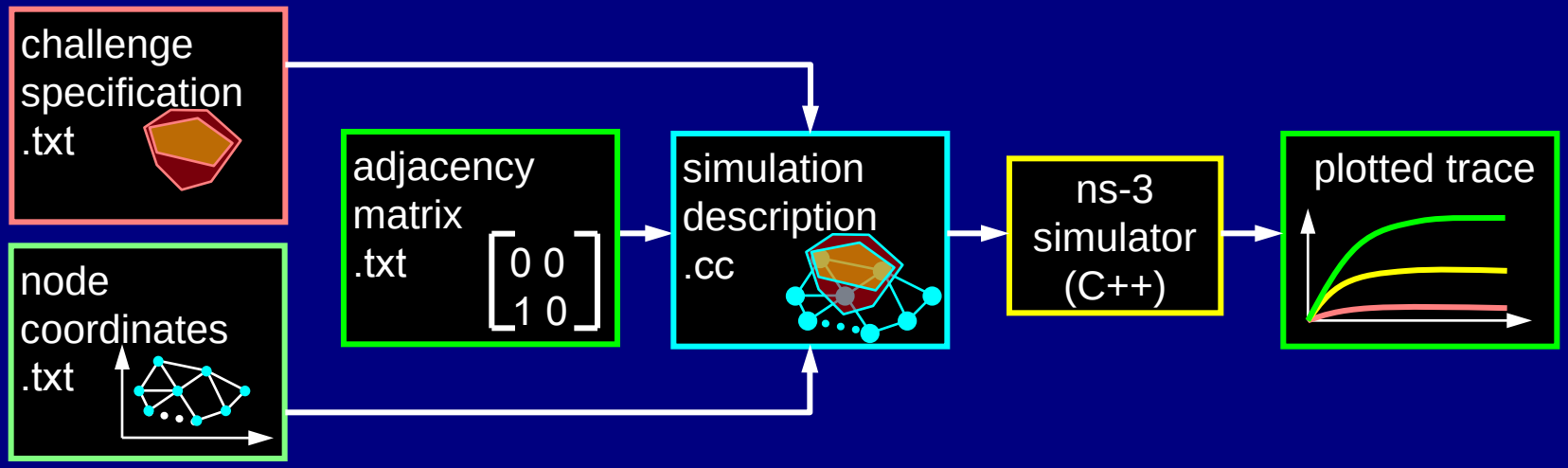
KU-TopView Topology Viewer



L1 Sprint fiber

L3 ISP

Challenge Simulation
KU-CSM

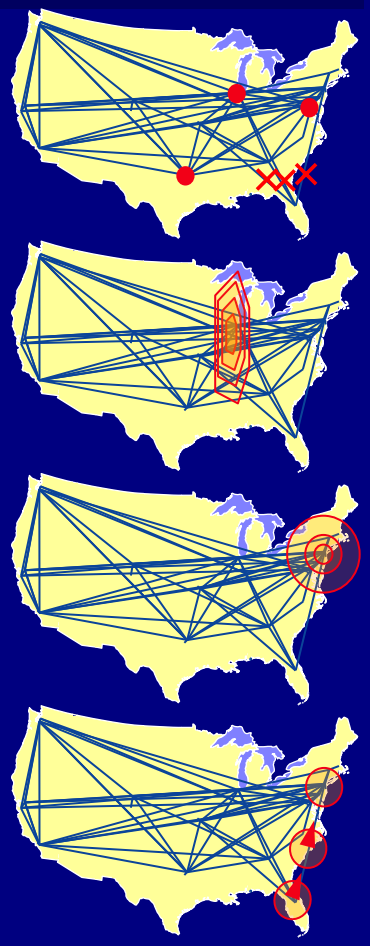


- KU-CSM Challenge Simulation Module
  - challenge specification describes challenge scenario
  - network coordinates provide node geo-locations
  - adjacency matrix specifies link connectivity
  - input to conventional ns-3 simulation run
  - generates trace to plot results with KU-gpWrapper [RNDM 2010]

KU-LoCGen

Challenge Simulation
Challenge Types

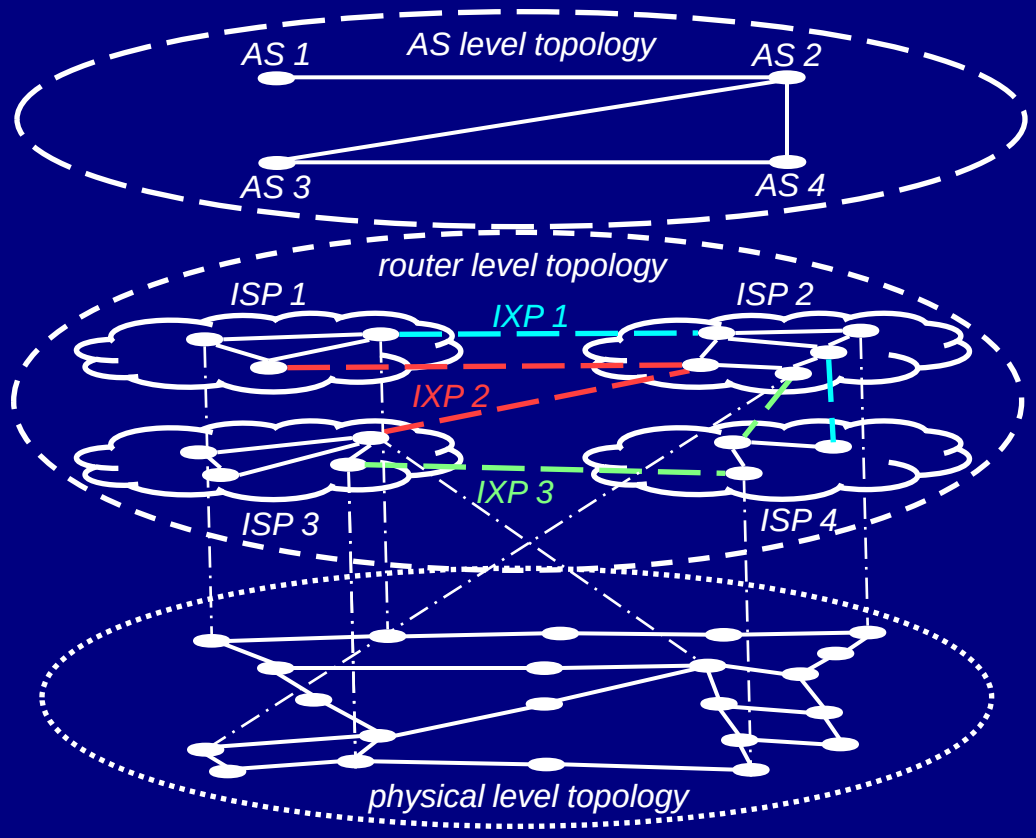
- Challenge types
  - node or link down
    - random or attack (deg, betweenness, …)
  - area based challenge
    - n-sided polygon: (x_0,y_0), … (x_{n-1},y_{n-1})
    - circle centered at (x_0,y_0) with radius r
  - wireless link attenuation or jamming
  - traffic attacks (DoS and DDoS)
- Challenge characteristics
  - type (e.g. wired/wireless)
  - class (e.g. important peering node)
  - dynamic: interval (t_i, t_j), trajectory



Multilevel Structural Diversity
Resistance to Attackers

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

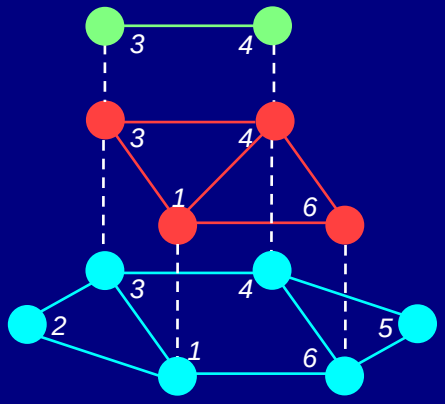
Multilevel Network Analysis
Abstraction of Internet Topology



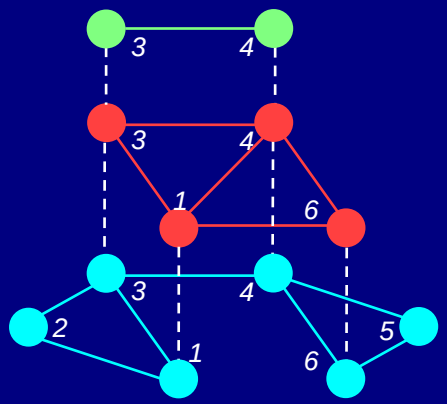
[DRCN 2013]

Multilevel Network Analysis

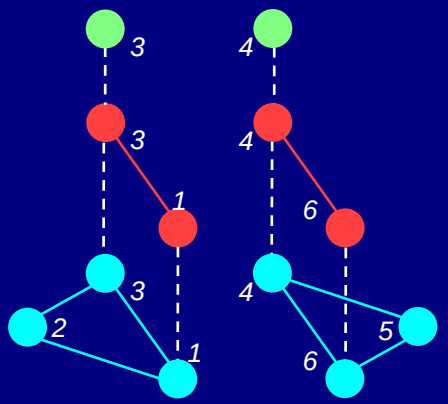
Multilevel Graph Model



Connected network



Disconnected network



Partitioned network

- Multilevel model for unweighted & undirected graphs
- Two requirements for multilevel graph model:
  - nodes at the above level are subset of lower level
  - nodes that are disconnected below are disconnected above

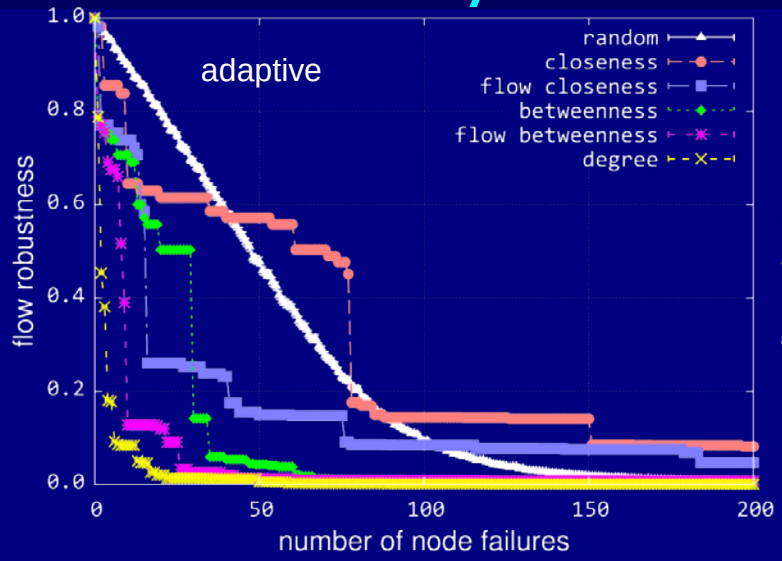
Resilience Analysis

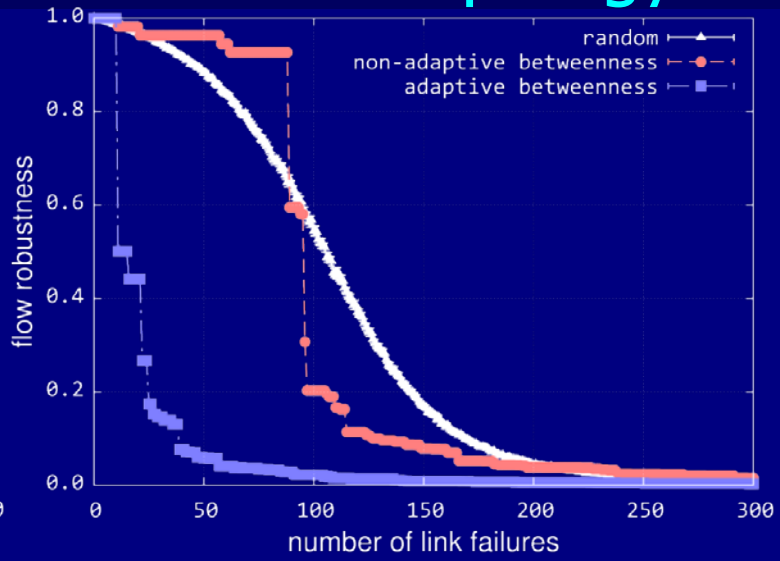
Graph-Theoretic Properties of Networks

Topology	Sprint Physical	Sprint Logical	AT&T Physical	AT&T Logical	US Highways
Number of nodes	263	28	361	107	400
Number of links	311	76	466	140	540
Maximum degree	6	14	7	23	7
Average degree	2.37	5.43	2.58	2.62	2.7
Degree assortativity	-0.17	-0.23	-0.16	-0.4	0.11
Node closeness	0.07	0.48	0.08	0.3	0.08
Clustering coefficient	0.03	0.41	0.05	0.09	0.05
Algebraic connectivity	0.0053	0.6844	0.0061	0.1324	0.0059
Network diameter	37	4	37	6	40
Network radius	19	2	19	3	21
Average hop count	14.78	2.19	13.57	3.38	13.34
Node betweenness	11159	100	15970	2168	22798
Link betweenness	9501	27	14270	661	18585

Multilevel Resilience

Effect of Physical Failures on L3 Topology

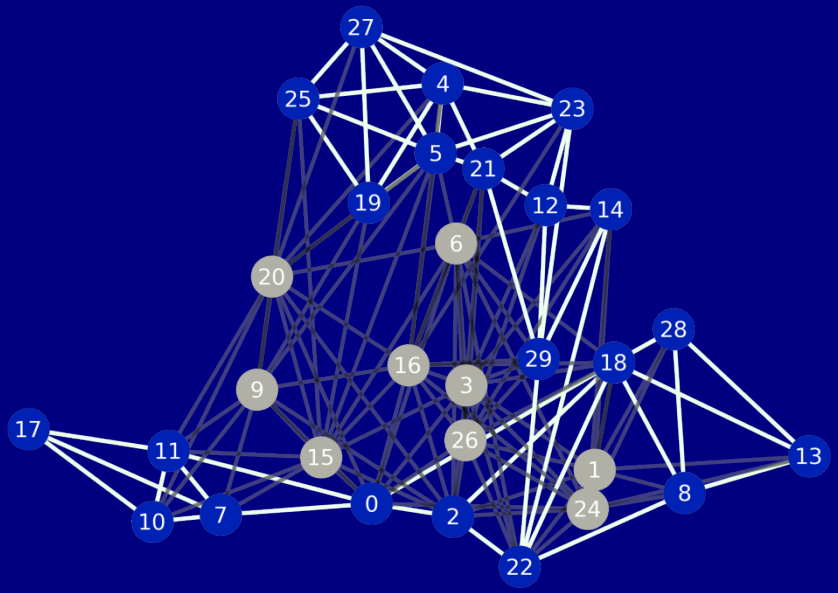


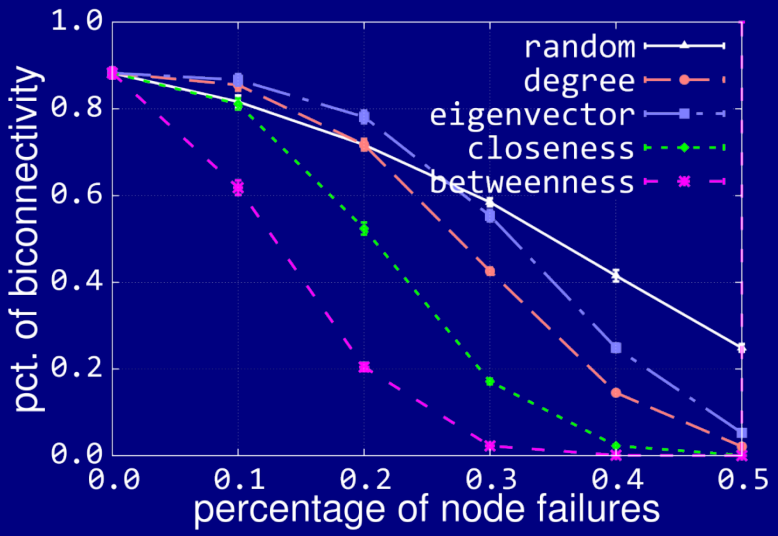


- Attacks against physical infrastructure
  - based on centrality (importance) metrics
  - adaptive recomputes metrics after each node failure)
- Analysis of impact on higher layer flows
  - heuristics to add elements under cost constraints

Dynamic Network Analysis
Attacks Against Critical MANET Nodes

- Dense network with relative large number of nodes
  - network connected after removal of high degree nodes (shown as grey nodes)



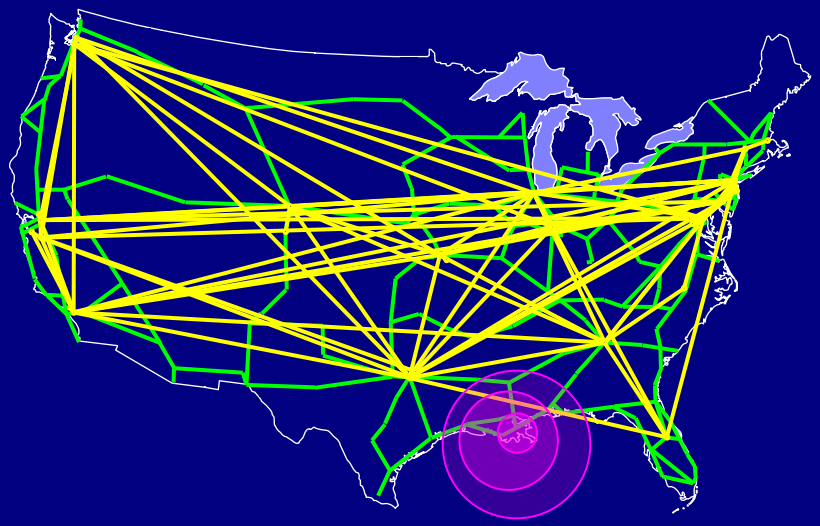


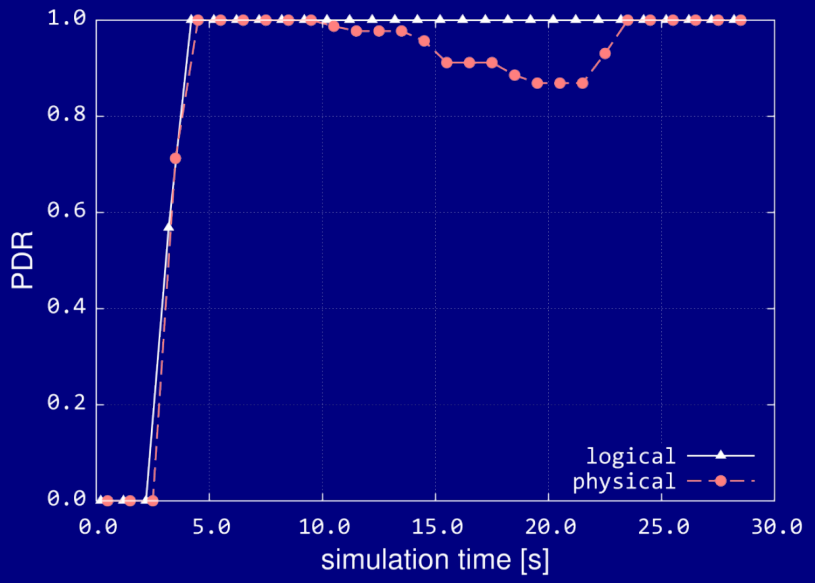
[RNDM 2013]

Multilevel Structural Diversity
Resilience to Large-Scale Disasters

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

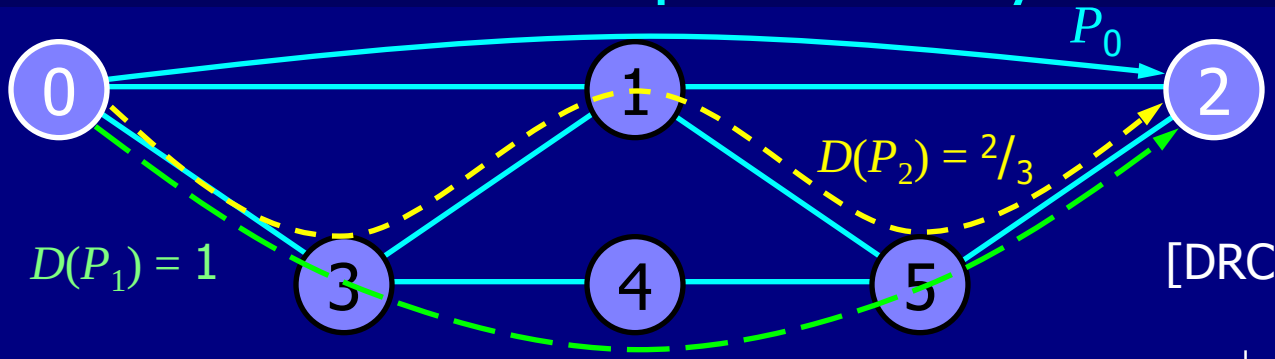
Simulation Analysis
Example: Multilevel Analysis of Disaster





- Hurricane disaster in New Orleans area
- Destruction of physical infrastructure
- Effect on IP-layer network services

Resilience Analysis
Path and Graph Diversity



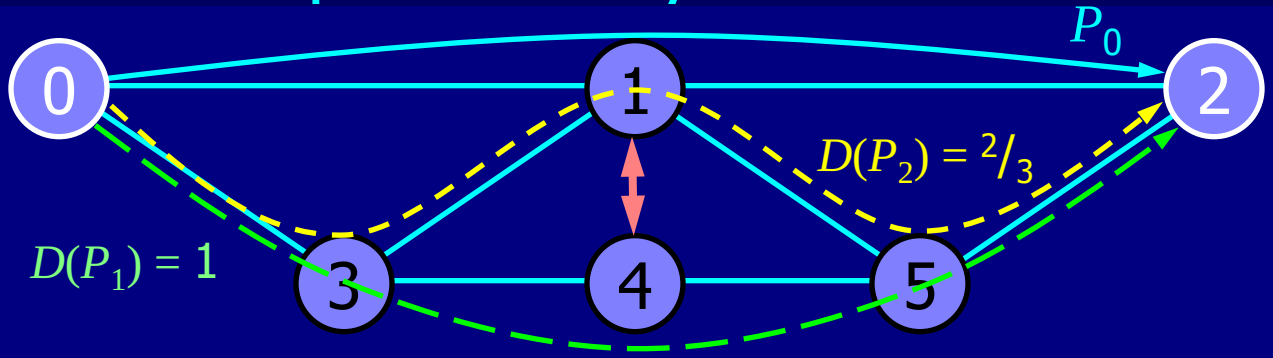
[DRCN 2009]

- Path diversity
  - measure of links and nodes in common

$$D(P_k) = 1 - \frac{|P_k \cap P_0|}{|P_0|}$$

- EPD: effective path diversity [0,1)
  - normalised diversity with respect to a single shortest path
  - measure of E2E flow resilience
- TGD: total graph diversity is average of EPD
  - for all pairs: quantifies available diversity in graph

Resilience Analysis
Path and Graph Diversity with Distance Metric



- cTGD: compensated TGD
  - weighted to be predictive of flow robustness [RNDM 2010]
  - algebraic connectivity also fair predictor or flow robustness
- GeoPath diversity
  - distance d between paths beyond source and destination
  - GeoResLSR: $(k, d, [s,t])$ multipath geographic routing
    - number of paths k

Resilience Analysis
Compensated Total Graph Diversity

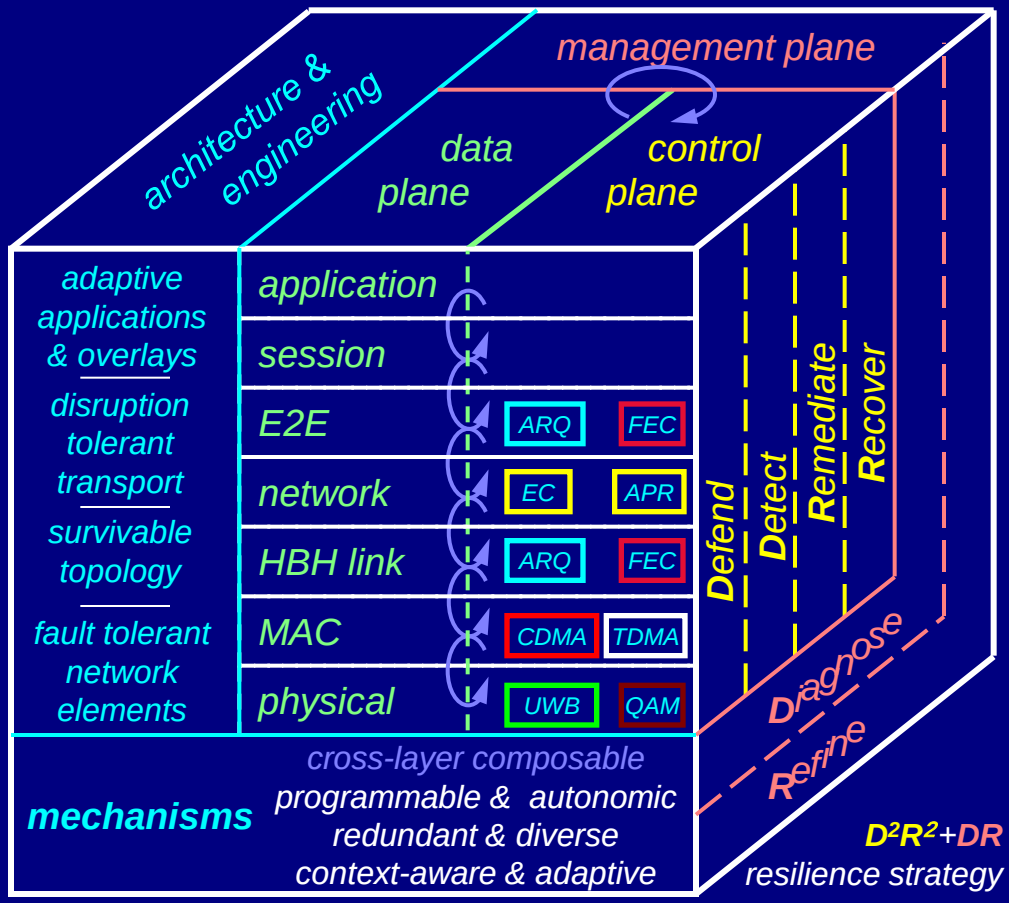
Metric Network	surv	deg	c TGD	TGD	clus coef	dia	hop cnt	clse	nod btw	link btw
full mesh	01	01	01	01	01	01	01	01	01	01
Level3	02	02	02	02	02	04	02	03	10	09
AboveNet	03	03	03	08	03	03	03	02	05	03
. . .										
ring	15	07	15	13	15	09	15	15	04	08
AT&T L1	16	07	16	03	13	10	16	16	15	17
Sprint L1	17	07	17	06	14	10	17	17	12	16

- cTGD much better predictor of flow robustness
  - cTGD with $\alpha = 0.25$ perfect predictor for these 17
    - 13 real networks plus 4 regular topologies

[RNDM 2011]

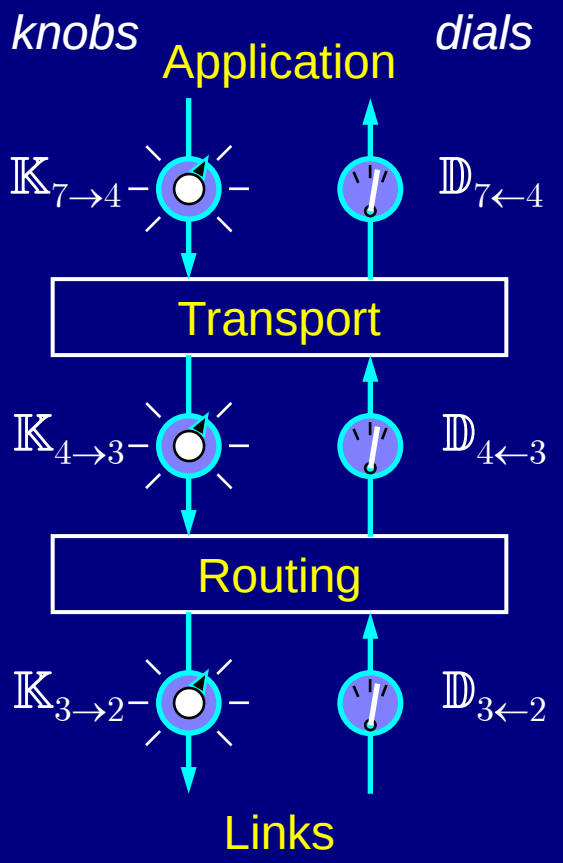
Resilient Networks
ResiliNets Architectural Model

- ResiliNets Cube
  - multilevel
    - protocol layers
    - planes
    - mechanisms
- D^2R^2+DR strategy
  - defend
  - detect
  - remediate
  - recover
  - diagnose
  - refine



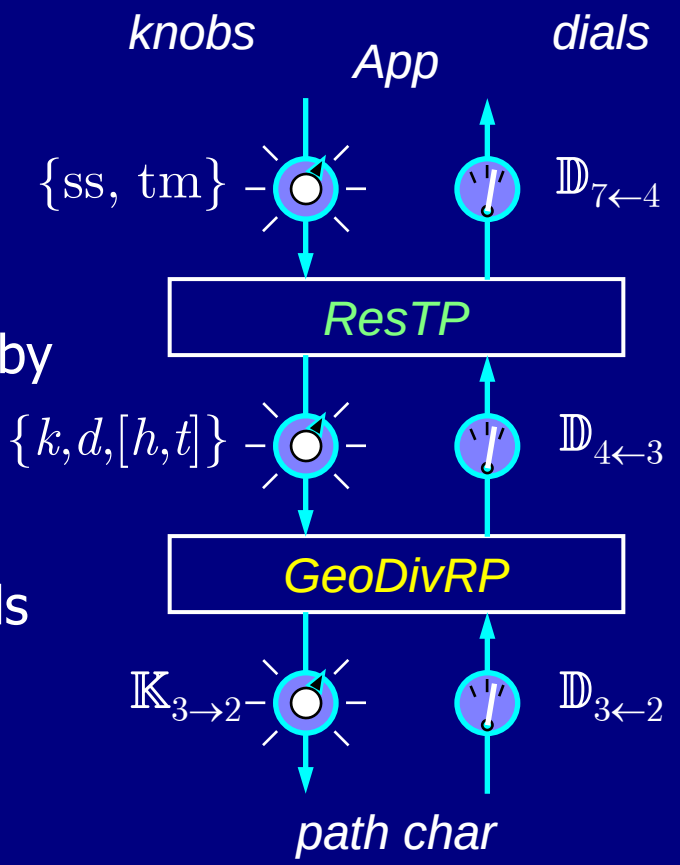
ResiliNets Protocols
Cross-Layer Model: Generic

- *Knobs* $\mathbb{K}_{i \rightarrow i-1} = \{k_i\}$ influence behaviour to levels below
- *Dials* $\mathbb{D}_{i+1 \leftarrow i} = \{d_i\}$ expose characteristics to upper levels
- Levels (of significance to ResiliNets)
  - 8: social
  - 7: application
  - 4: end-to-end transport
  - 3i: inter-realm (domain)
  - 3r: routing
  - 3t: logical topology
  - 2: hop-by-hop links
  - 1: physical topology

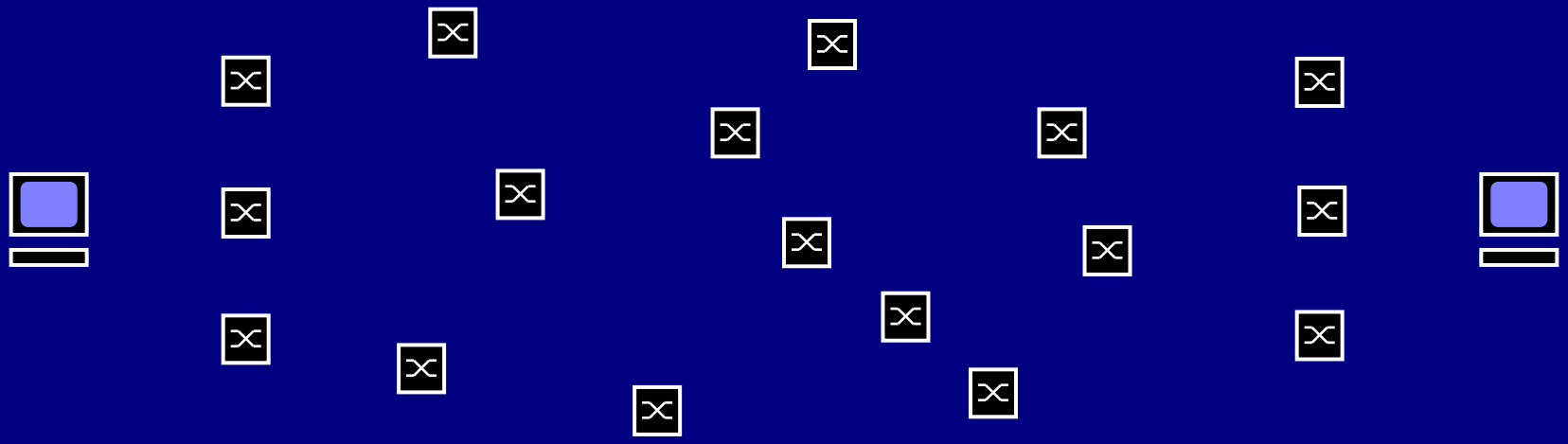


ResiliNets Protocols
Cross-Layer Model: ResTP/GeoDivRP

- Application
  - $\mathbb{K}_{7\to4} = \{\mathrm{ss}, \mathrm{tm}\}$
    service spec and threat model
- E2E Transport: ResTP
  - erasure spreading vs. hot standby
  - FEC vs. HARQ vs. ARQ
  - $\mathbb{K}_{4\to3} = \{k,\ d,\ [h,\ t]\}$
    k-path diversity over distance d
    opt. stretch h and skew t bounds
- Routing: GeoResLSR
  - construct k d-diverse paths

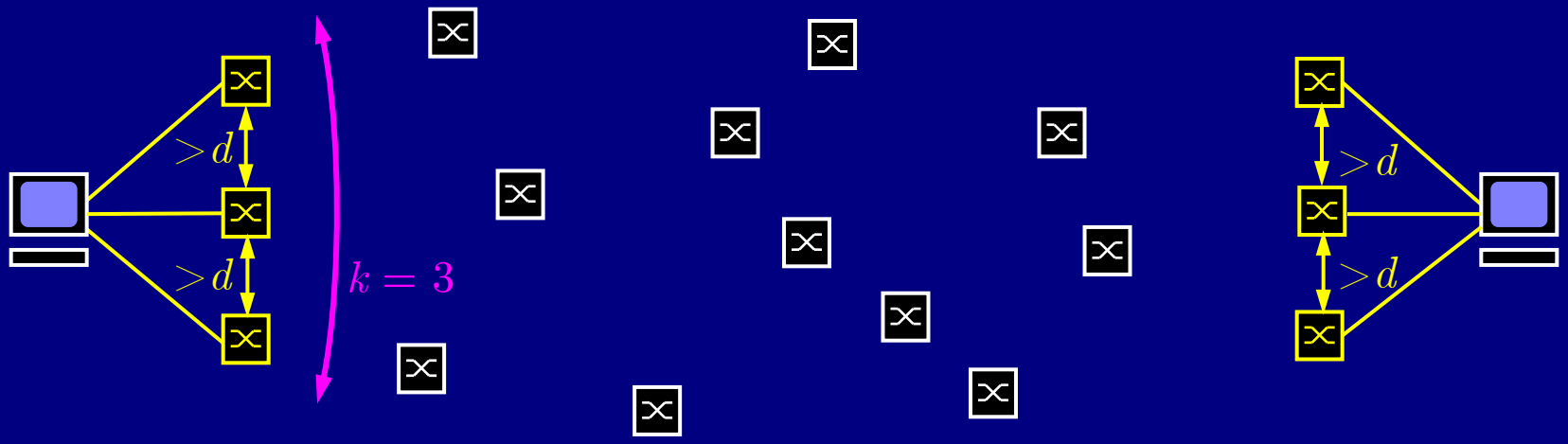


ResiliNets Protocols
GeoDivRP



- GeoDivRP: intermediate waypoint algorithm
  - LSAs contain geolocation of routers

ResiliNets Protocols
GeoDivRP



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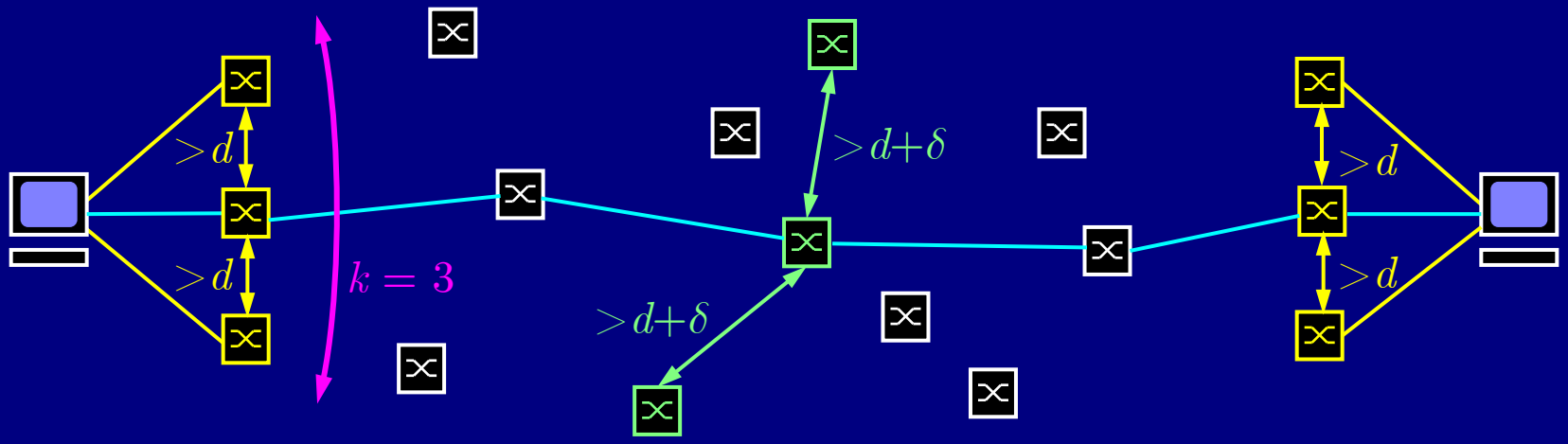
  - choose k next hop routers at least d apart if possible

ResiliNets Protocols
GeoDivRP



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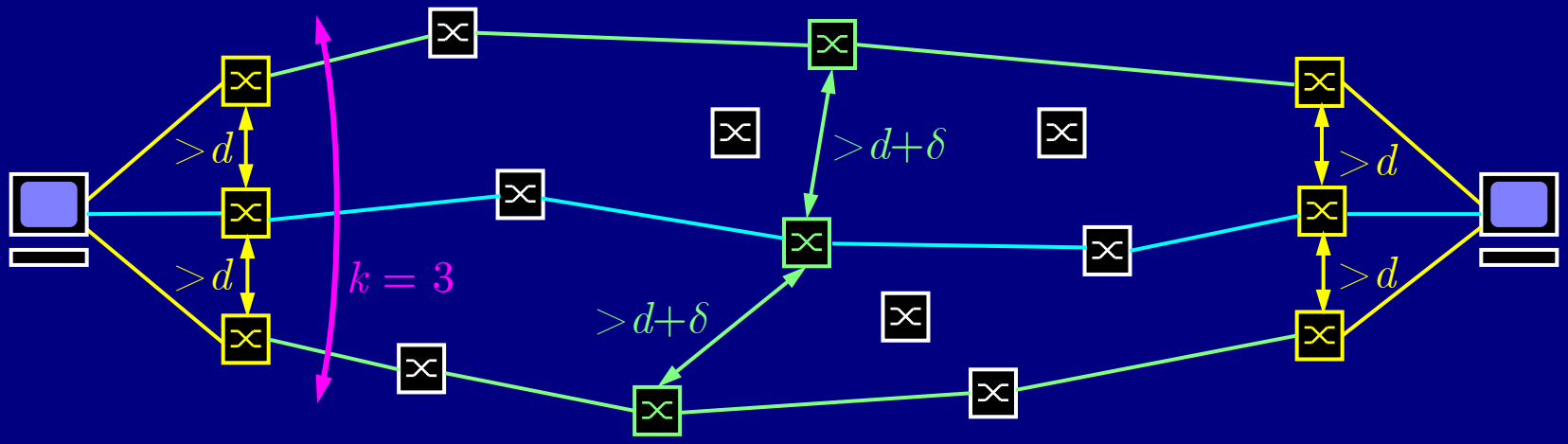
  - choose mid-point waypoints $d+\delta$ wrt to shortest path
    - limit stretch to h and skew to t if specified and possible

ResiliNets Protocols
GeoDivRP



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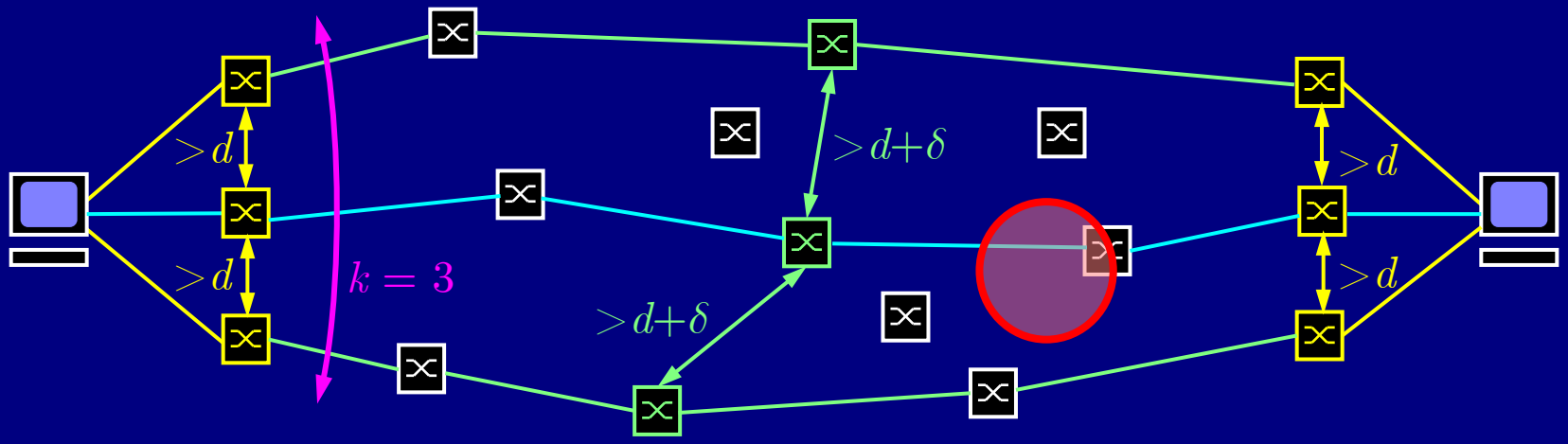
ResiliNets Protocols
GeoDivRP



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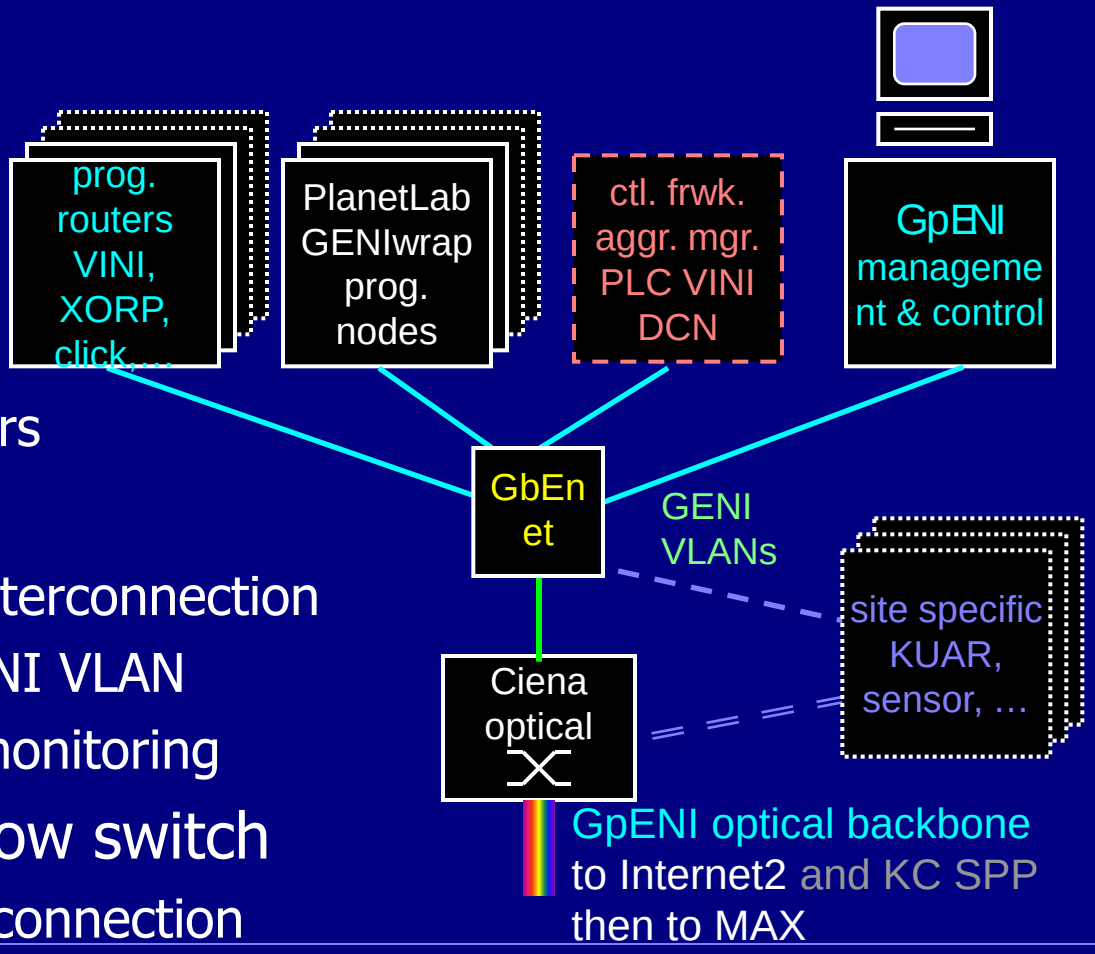
Multilevel Structural Diversity
Experimental Evaulation

- ResiliNets review
- Challenge Taxonomy
- Multilevel interrealm resilience
  - resilience to attackers
  - resilience to large scale disasters
- Experimental evaluation

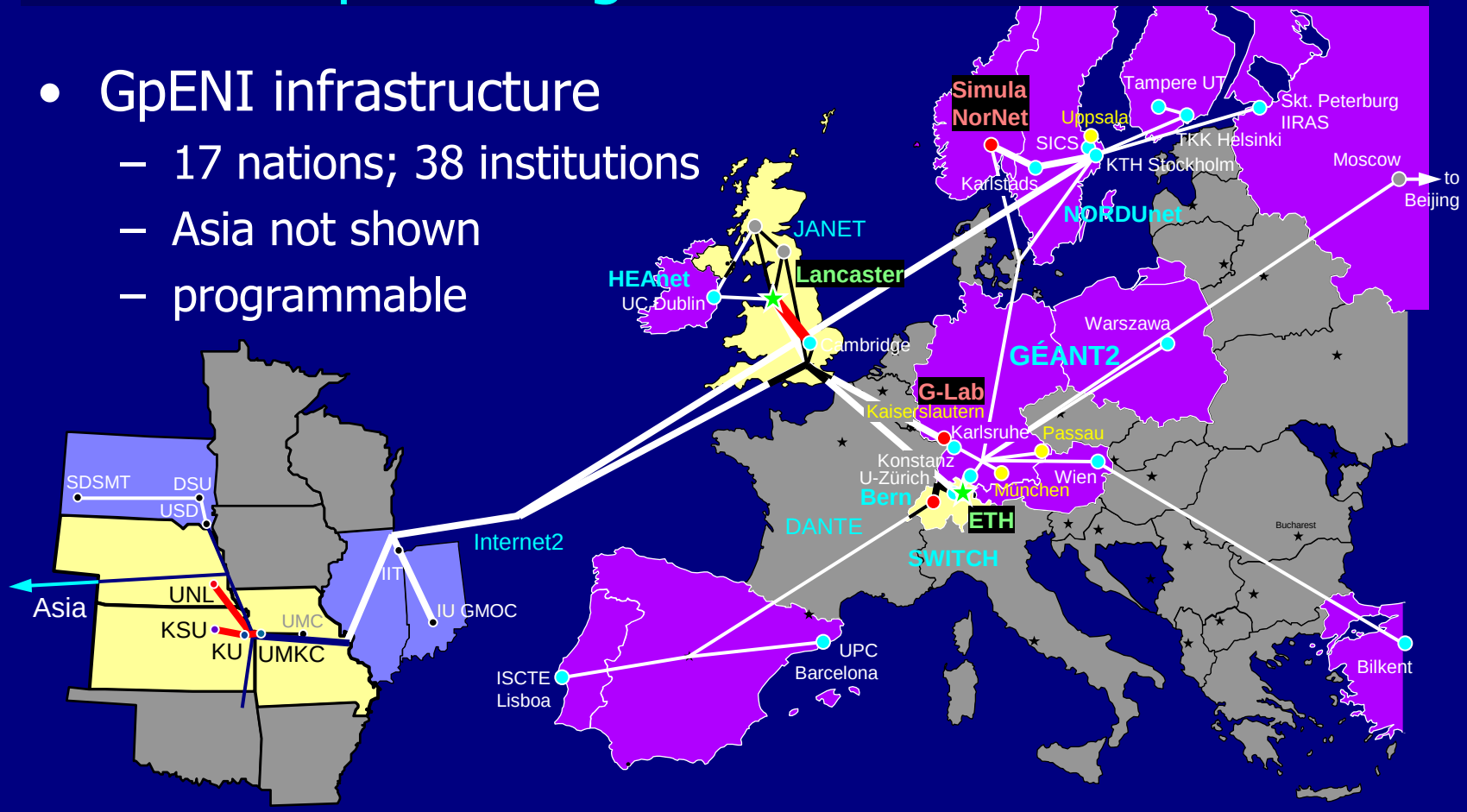
Experimental Analysis
GpENI Node Cluster

- GpENI cluster
- 5–10 PCs
  - GpENI mgt.
  - L4: PlanetLab
  - L3: prog. routers
- GbE switch
  - arbitrary site interconnection
  - L2: GpENI/GENI VLAN
  - SNMP cluster monitoring
- Brocade Openflow switch
  - L1 GpENI interconnection



Experimental Analysis
GpENI Programmable Testbed

- GpENI infrastructure
  - 17 nations; 38 institutions
  - Asia not shown
  - programmable

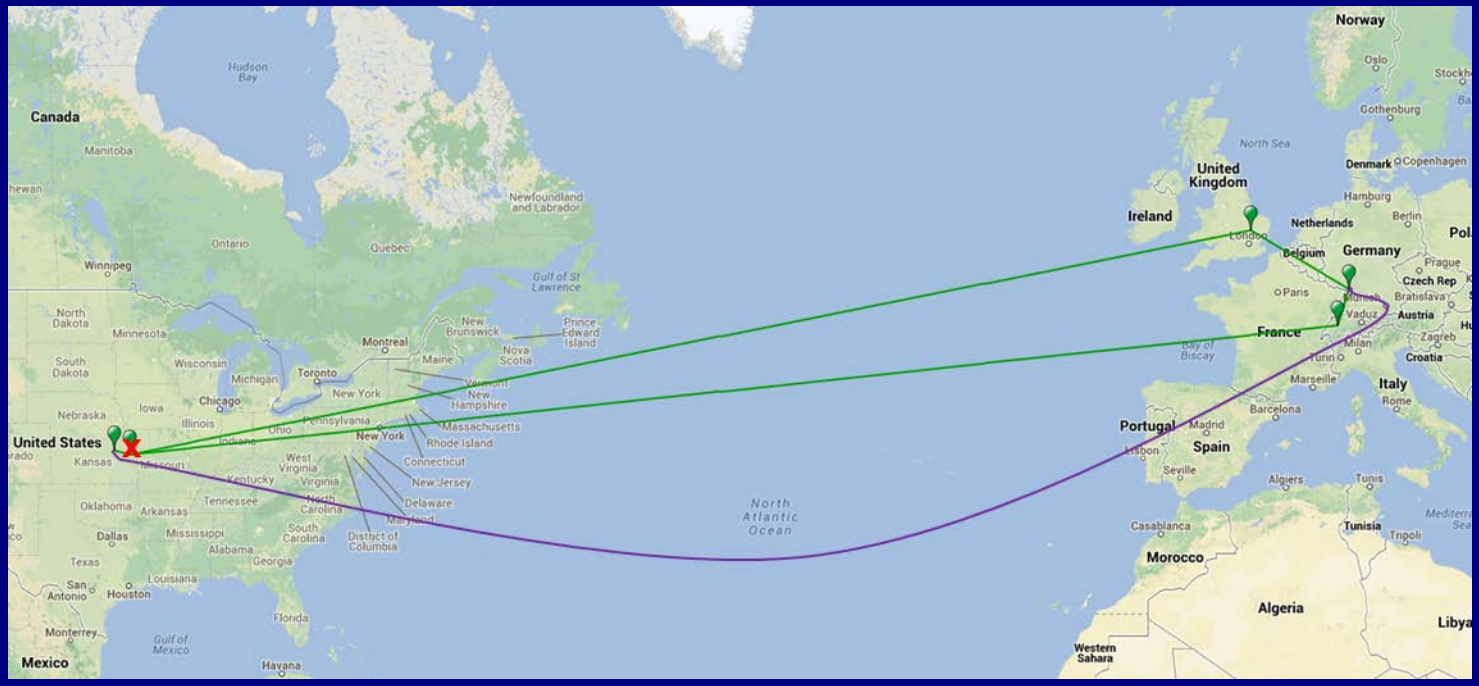


Resilience Experimentation on GpENI

Overview

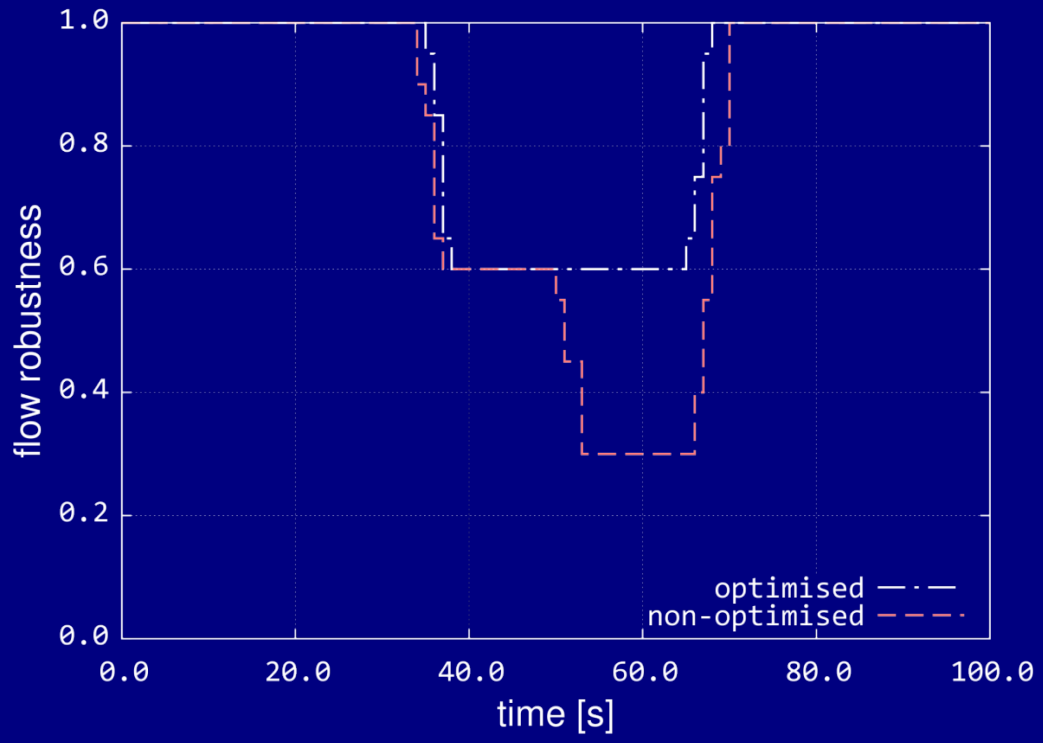
- Used 5 GpENI sites: KU, KSU, Cambridge, Bern, KIT
- Topologies constructed between PlanetLab nodes
  - tinc VPN software to control topology and failures [tinc]
- Utilised optimisation algorithm that adds link: [RNDM 2013]
  - most algebraic connectivity increase
  - least cost incurred
- Evaluate network performance
  - in terms of flow robustness
  - pings between node pairs
  - link taken down for ~ 30 s

Experimentation Scenario 2
Partial-Mesh Topology



- Highest-degree node (KU, USA) is attacked
- Optimised topology has link between KSU/USA-KIT/DE

Experimentation Result 2
Partial-Mesh Topology



- Algebraic-connectivity optimised topology performs better

End