Modelling communication network challenges for Future Internet resilience, survivability, and disruption tolerance: a simulation-based approach

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Abstract Communication networks play a vital role in our daily lives and they have become a *critical infrastructure*. However, networks in general, and the Internet in particular face a number of challenges to normal operation, including attacks and large-scale disasters, as well as due to mobility and the characteristics of wireless communication channels. Understanding network challenges and their impact can help us to optimise existing networks and improve the design of future networks; therefore it is imperative to have a framework and methodology to study them. In this paper, we present a framework to evaluate network dependability and performability in the face of challenges. We use a simulation-based approach to analyse the effects of perturbations to normal operation of networks. We analyse Sprint logical and physical topologies, synthetically generated topologies, and present a wireless example to demonstrate a wide spectrum of challenges. This framework can simulate challenges on logical or physical topologies with realistic node coordinates using the ns-3 discrete event simulator. The framework models failures, which can be static or dynamic that can temporally and spatially evolve. We show that the impact of network challenges depends on the duration, the number of network elements in a challenge area, and the importance of the nodes in a challenge area. We also show the differences between modelling the logical router-level and physical topologies. Finally, we discuss mitigation strategies to alleviate the impact of challenges.

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1 Introduction and motivation

Communication networks have evolved tremendously over the past several decades, offering a multitude of services while becoming an essential critical infrastructure in our daily lives. While this evolution is still progressing, user expectations from these networks are increasing in terms of performance and dependability. On the other hand, achieving fully resilient networks is practically impossible, in part due to cost constraints, and therefore networks experience disruptions. We define *resilience* as the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation [79, 80]; resilience is a discipline that subsumes survivability, fault tolerance, disruption tolerance, dependability, performability, and security.

Understanding network behaviour under perturbations can improve today's networks performance, as well as lead

to a more resilient and survivable Future Internet. Therefore, it is essential to have a thorough understanding of the network behaviour when exposed to challenges, such as component failures, attacks, large-scale disasters, and effects of the mobile wireless communication environment.

Recognition of network disruptions and their causes is crucial for planning and designing networks. Some challenges to the network are inherent in the communication environment, in particular the weak and intermittent connectivity of wireless channels and dynamic topologies due to mobility. Attacks against the network are frequent, and there are also challenges caused by acts of nature such as hurricanes and solar storms. Additionally, networks are built by humans and are not completely resilient due to design flaws and cost constraints. The redundancy and diversity that increase resilience add to the cost of the network. Therefore, we need to understand the challenges and their impact on network operation and the service delivered to users.

We cannot thoroughly study the effects of challenges in live networks without impacting users. Testbeds are useful, but do not provide the scope and scale necessary to understand the resilience of large, complex networks, although progress is being made in this direction [82, 83]. Simulations arguably provide the best compromise between tractability and realism to study challenges, however this is nontrivial [60].

In this paper, we present a framework to understand network behaviour when faced by challenges to communication networks. Different forms of challenges impose varying impacts, therefore they need to be modelled accordingly. Therefore, we present models to represent the various forms of challenges and show simulation results of network performance when exposed to examples of such challenges. Although we present the challenges and study the impacts on communication networks, this framework can be useful in analysis of other networks.

The rest of the paper is organised as follows: We describe challenges in communication networks and categorise them in Sect. 2. The evaluation methodology and implementation of challenge models are presented in Sect. 3. Related work is described in Sect. 4, followed by the simulation results in Sect. 5. The impact of geographically correlated failures on physical networks is presented in Sect. 6. We discuss challenge models and mitigation techniques in Sect. 7. Lastly, we summarise our findings as well as propose future work in Sect. 8.

2 Network challenge models

A *challenge* is an event that impacts normal operation of the network [80]. A *threat* is a potential challenge that might exploit a *vulnerability*. A challenge triggers *faults*,
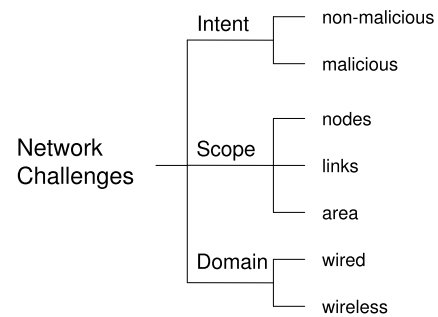
Fig. 1 Taxonomy of network challenges

which are the hypothesized cause of *errors*. Eventually, a fault may manifest itself as an error. If the error propagates it may cause the delivered services to *fail* [7]. Challenges to the normal operation of networks include unintentional misconfiguration or operational mistakes, malicious attacks, large-scale disasters, and environmental challenges [31, 33, 78, 80, 81]. Network challenges can be categorised based on the intent, scope, and domain they impact. The network challenge taxonomy used for our simulation framework is shown in Fig. 1.

It is essential to differentiate the challenges exposed and understand their impact. Next, we present the modelling of various challenges, grouped into three categories: intent, scope, and domain.

2.1 Challenge models based on intent

We model the challenges based on the *intent* as malicious or non-malicious. Non-malicious challenges can be due to incompetence of an operator (e.g. accidental fiber cut, misconfiguration of network resources, large-scale outage due to power failure) or designer (e.g. hardware or software faults eventually causing a node or a link to fail). These random events affect node and link dependability, and result in the majority of the failures observed [28, 45, 65]. On the other hand, malicious attacks, orchestrated by an intelligent adversary, target *specific* parts of a network and can have significant impact if critical elements of the network fail. Note that while it is important to distinguish the intent in designing challenge models, the effect on network operations may be indistinguishable between malicious and non-malicious challenges.

2.2 Challenge models based on scope

The *scope* of a challenge can be further categorised based on nodes, links, or network elements affected within a geographic area. While node and link failures can impact single or multiple network elements, area-based challenges usually affect multiple network elements. Natural phenomenon

Table 1 Examples of network challenges

Challenge examples	Intent		Scope			Domain	
	Non-malicious	Malicious	Nodes	Links	Area	Wired	Wireless
Natural component failures [45, 65]	×		×	×		×	×
Misconfiguration [50, 57, 67]	×		×	×	×	×	×
Cable cuts [27, 68, 72, 84]	×	×		×		×	
Jammers [81]		×	×	×			×
Interference [81]	×			×			×
Weather precipitation [38]	×			×	×		×
Attack against key infrastructure components [48, 71]		×	×	×		×	×
Natural disasters [22, 25, 42, 66]	×				×	×	×
Pandemic [3, 4]	×	×			×	×	×
Nationwide Internet outage [20, 21, 23, 24, 48, 68]	×	×			×	×	×
Power failure [19, 26]	×				×	×	×
EMP weapon [2]		×			×	×	×
Coronal mass ejection [5]	×				×	×	×

that are geographically correlated can impact quite large areas. Hurricanes, earthquakes, and solar storms are examples of natural disasters that can impact the network at a large scale [5, 42, 58, 66]. Malicious area-based challenges include electromagnetic pulse weapons [2]. Furthermore, geographically correlated failures can be due to dependency among critical infrastructures, as experienced in the 2003 Northeast power blackout in the US [26, 46].

2.3 Challenge models based on domain

Networks have quite different characteristics based on the wired or wireless domain in which they operate. Communication network performance in the wireless domain is primarily affected by the mobility of the nodes and the impairments caused by the wireless medium. The challenges that are inherent in the wireless domain include weakly, intermittently, and asymmetrically connected channels, mobility of nodes in a MANET (mobile ad-hoc network), and unpredictably long delays, particularly with store-and-forward or store-and-haul disruption tolerant networks (DTN) [32, 80, 81]. These are the natural result of noise, interference, and other effects of RF propagation such as scattering and multipath, as well as the mobility of wireless nodes. Furthermore, weather events such as rain and snow can cause the signals to attenuate and impair the wireless communication network [38]. Malicious nodes may jam the signal of legitimate users to impair communication in the open wireless medium.

While the above-mentioned challenge models are orthogonal to each other, challenge scenarios are a combination of challenge sub-categories. For example, a failure due to natural aging of a component can be categorised as a non-

malicious, wired (or wireless), node failure. Examples of challenges with this taxonomy are listed in Table 1.

3 Simulation framework

In this section, we present our simulation framework to evaluate the resilience of network topologies when subject to a variety of challenges. The challenge simulation models are developed in the ns-3 [62] network simulator. Network configuration and challenge specification files are fed to our preprocessor that is the input to an ns-3 simulation.

3.1 Methodology overview

Simulation via abstraction is one of the techniques to analyse networks in a cost-effective manner. We have chosen ns-3 [62] since it is open source, flexible, provides mixed wired and wireless capability (unlike ns-2 [61]), and the models can be extended. Unfortunately, the simulation model space increases multiplicatively with the different number of challenges and network topologies being simulated. Hence, for n different topologies subjected to c different challenges, $n \times c$ models must be generated and simulated. Our framework decouples the challenge generation from topologies by providing a comprehensive challenge specification framework, thereby reducing the simulation model space to n network $+ c$ challenge models. We have created an automated simulation model generator that will combine any recognised challenge specifications with any provided topology, thus increasing the efficiency of simulation generation. Our simulation framework consists of four distinct steps as shown in Fig. 2.

Fig. 2 Framework flow
diagram
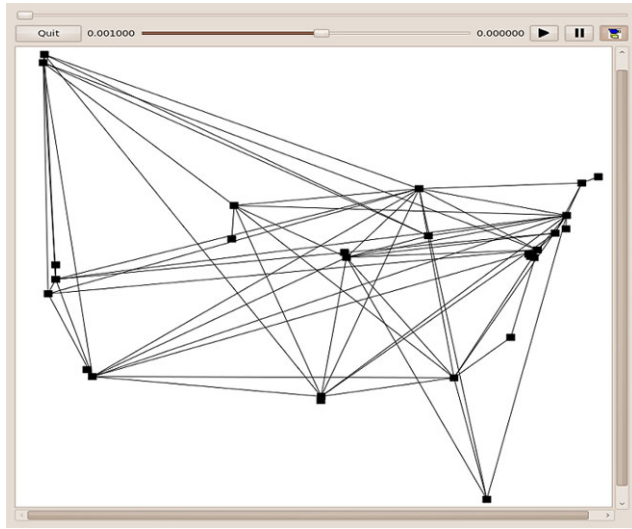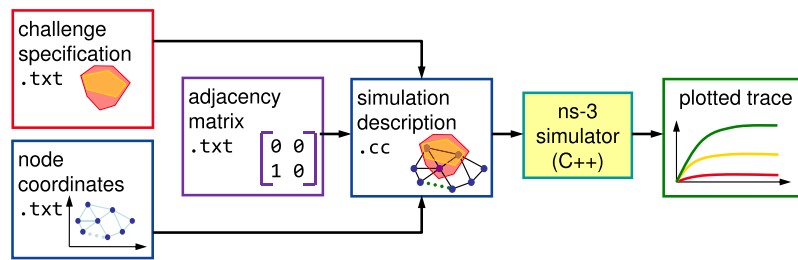
Fig. 3 NetAnim screen shot of inferred Sprint topology

The first step is to provide a challenge specification that
includes the type of the challenge and configuration of the
challenge scenario. The second step is to provide a descrip-
tion of the network topology, consisting of node geograph-
ical or logical coordinates and an adjacency matrix. The
third step is the automated generation of ns-3 simulation
`C++` code based on the topology and challenge descrip-
tor. Finally, we run the simulations and analyse the network
performance throughout the challenge scenario. Addition-
ally, the simulation framework can also be enabled to gen-
erate ns-3 network animator (NetAnim) traces for visualisa-
tion purposes. A NetAnim screenshot of the Rocketfuel [76]
based Sprint backbone network topology of 27 nodes and
68 links is shown in Fig. 3. We have provided partial sim-
ulation code to ns-3 community that automates generation
of topologies based on an adjacency matrix and node co-
ordinates [14], which has been incorporated to the ns-3.10
standard release. Eventually, we will release the complete
code base that simulates network challenges.

3.2 Implementation of challenge models

In the following subsections we present the details of im-
plementation of challenge models in the ns-3 discrete event
simulator.

3.2.1 Non-malicious challenges

In the case of wired domain challenges in this category, the
number of nodes or links k subject to random failure during
a challenge period (t_1, t_2) is listed in the challenge specifi-
cation file. Nodes or links are shut down for the duration of
the challenge if the probability of failure of that node or link
is greater than the probabilistic failure rate threshold p_r pro-
vided as a parameter. This type of challenge models random
node and link failures that are uncorrelated with respect to
topology and geography.

3.2.2 Malicious attacks

Malicious attacks result from the exploitation of structural
knowledge of the network by an attacker who wishes to in-
flict maximum damage with limited resources. We use topo-
logical properties of the graph in order to determine the
critical elements in the network, based on measures such
as the degree of connectivity of nodes, and betweenness
of nodes and links (betweenness is the number of shortest
paths through a particular element [49]). The critical nodes
or links are shut down for the duration of the challenge pe-
riod (t_1, t_2).

3.2.3 Large-scale disasters

The challenge specification for area-based challenges result-
ing from large-scale disasters is an n-sided polygon with
vertices located at a particular set of geographic coordi-
nates (x_i, y_i) or a circle centered at specified coordinates
(x_c, y_c) with radius r. The simulation framework then de-
termines the nodes and links that are encompassed by the
polygon or circle, and disables them during the challenge
interval. We use the Computational Geometry Algorithms
Library (CGAL) [1], which is an open source library with
efficient geometric algorithms implemented in `C++`. We
also implement dynamic area-based challenges, in which
the challenge area can evolve in shape over time: scale (ex-
pand or contract), rotate, and move on a trajectory during
the simulation. Large-scale regional failure scenarios previ-
ously only have been modelled as a static circle [8] for eval-
uating the performance of path restoration after a failure.
Examples of the need to simulate arbitrary polygons are to

model large-scale power blackouts, EMP weapons [2], coronal mass ejections [5], and large-scale natural disasters such as hurricanes and tsunami.

3.2.4 Wireless challenges

To simulate challenges in the wireless domain, we have created a new ns-3 propagation loss model that includes a mobility model parameter (e.g. random waypoint [12] or Gauss-Markov [10]) and range of influence. Using these parameters, the user can specify where the loss takes place and how it moves over time. In this way, we model a realistic challenge instead of relying solely upon statistical methods. Unlike signal loss due to scattering and line-of-sight obstacles, jammers can cause radio interference that increases channel noise and reduces the SNR (signal-to-noise ratio) that is critical to a receiver's ability to discern the data bits correctly. We implement a jammer module that sends high power signals with high data rate frames continuously on a given channel.

4 Related work

Modelling and simulating network performance under challenge conditions is non-trivial [60]. There have been several studies that analyse different aspects of networks under challenges, however we believe this is the first unified framework that models a wide range of challenges.

Network topologies faced by random node or link failures have been studied [11, 18]. Network topologies faced by random and targeted attacks by degree of connectivity were shown to have local effect [29], since higher degree nodes that are access PoPs (Point of Presence) reside on the edge of the network. Statistical properties of logical topologies under degree-based attacks for static and dynamic evolving cases have been investigated [69, 70]. Vertex and edge attacks against the wired topologies have been studied [36, 55, 73, 85] were based on static and dynamic topologies, in which graph metrics (degree of connectivity and betweenness) are recalculated dynamically after the attacks. Distributed denial-of-service (DDoS) attacks have been simulated using the ns-2 simulator and performance of legitimate user bandwidth is analysed for different queueing algorithms [47], but DDoS attacks generally are not targeted against infrastructure such as routers.

Internet interdomain routing performance under regional failure scenarios has been studied and found that the impact of such failures is primarily due to failure of access links in the challenge area [90]. However, this lacks a regional challenge model that can temporally and spatially evolve. Survivability of large-scale regional failures has been modelled, considering the performance of path restoration after

a failure [8]. The failure scenarios consist of a regular circle centered at a point with constant radius R. In our framework the shape of failures are modelled either as a circle or as an n-sided polygon that can evolve over time.

Logical topologies can be useful to study random failures and their impacts. In our earlier work, we used logical topologies to analyse the performability of the networks under attacks [13, 51]. However, physical topologies are *necessary* to study the impact of geographically correlated failures. The reliability of physical networks under disasters was studied [58, 59], which presents algorithms that find a worst-case line segment and circular cut. However, disasters can take any form of shape in time and our framework can model irregular polygons dynamically.

A toolkit was previously implemented in ns-2 for simulating obstacles, however it lacks jammers and impairments [15, 16].

5 Simulation analysis

In this section, we apply our challenge framework and evaluation methodology to sample topologies to demonstrate the utility of this approach. We used ns-3.7.1 release and the simulation parameters are as follows: The network is composed of bidirectional wired links with 10 Mb/s bandwidth and 2 ms transmission delay. Routing is accomplished using the Dijkstra shortest-path-first algorithm, recalculated at each time step, with reconvergence delay as a simulation parameter. The traffic is constant bit rate (CBR) at 40 kb/s between every node pair, with 1000 Byte packets. These parameters are chosen such that there is no congestion under normal operation, but the network is not significantly over-provisioned so that we will see the effect of node and link failures. We measure the network's aggregate performance under challenges in terms of aggregate packet delivery ratio (PDR).
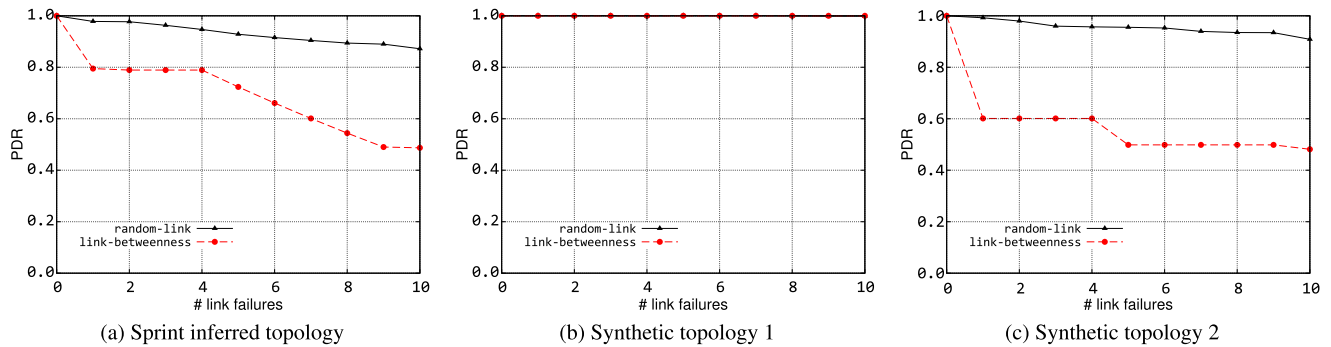
5.1 Non-malicious and malicious challenges

First, we evaluate the performance of three separate topologies shown in Fig. 4 under the presence of malicious and non-malicious challenges. The topologies we choose are the Sprint topology based on the Rocketfuel map [76] (Fig. 4a) and two synthetic topologies (Fig. 4b and 4c). The synthetic topologies are generated using the KU-LoCGen topology generation tool [35, 39, 77]. KU-LoCGen generates topologies with geographic constraints and places links between nodes using various models; in this case the modified Waxman [88] model. The resulting synthetic topologies have the same number of nodes at the same geographic locations as the inferred Sprint topology, however the number
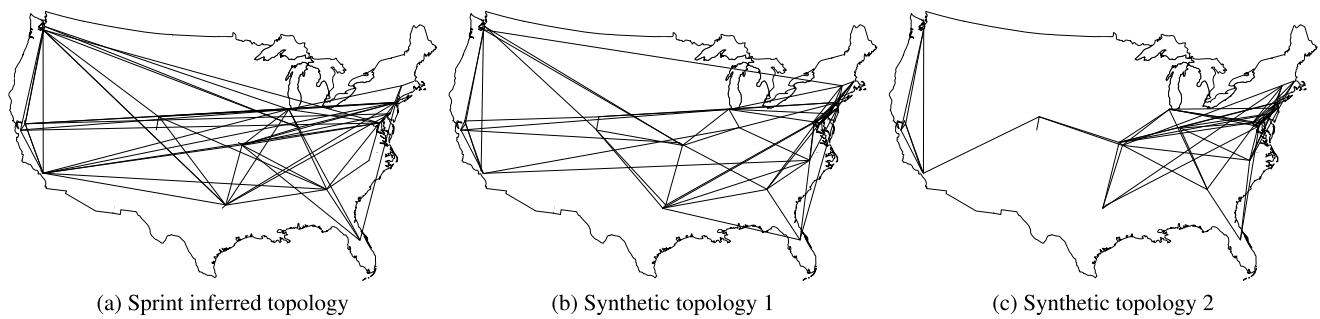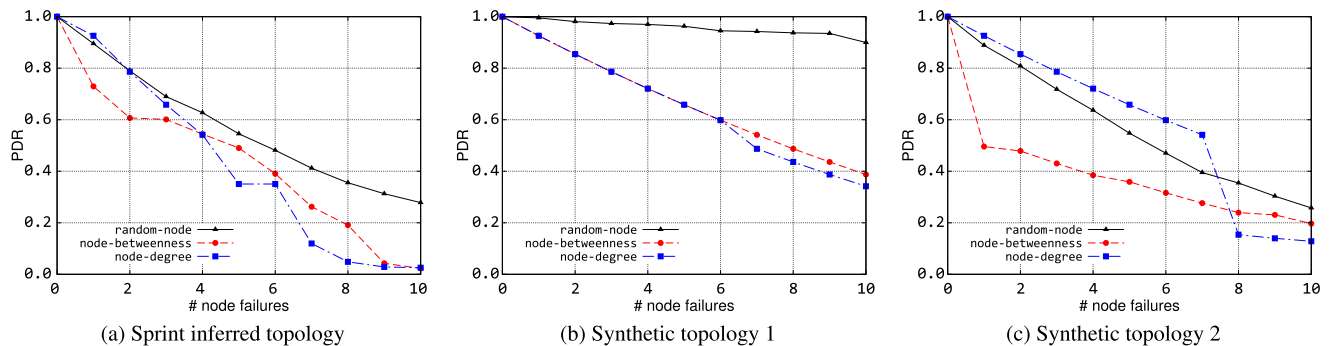
Fig. 4 Sample topologies for evaluation of node and link failures

Fig. 5 PDR during non-malicious and malicious link perturbations

Fig. 6 PDR during non-malicious and malicious node perturbations

of links and connectivity of the nodes differ. The two synthetic graphs chosen for this paper consist of a richly connected and poorly connected topology to demonstrate the range of robustness results from this simulation framework. The graph characteristics of three topologies are presented in Table 2.

We evaluate the performance of the sample topologies under the presence of malicious and non-malicious challenges with the PDR of the network shown in Fig. 5 for link failures and in Fig. 6 for node failures with up to 10 links or nodes down. We measure the instantaneous PDR at the steady-state condition during the challenges for each point. We also note that for random failures, we average the results over 100 runs with random seed generated based on the sys-

tem clock. For malicious challenges (betweenness or degree of connectivity), first we calculate the betweenness (or degree of connectivity) for each network element in the topology, and provide the challenge file as the list of the elements to be brought down in order as a function of the x-axis.

Figure 5 shows the PDR during the link perturbations to Sprint inferred (Fig. 5a), synthetic 1 (Fig. 5b), and synthetic 2 (Fig. 5c) topologies respectively. We evaluate the PDR during link failures for two cases: 10 random link failures and an attack using the 10 highest-ranked links based on link betweenness values. Except for the synthetic topology 1, intelligent link attacks have a more degrading impact than the random failures. The PDR of 100% for both random and attack cases for the synthetic 1 topology (Fig. 5b) can be at-

Table 2 Topological characteristics of sample networks

Network topology	Sprint	Synthetic 1	Synthetic 2
Number of nodes	27	27	27
Number of edges	68	74	68
Maximum degree	12	9	10
Average degree	5.04	5.5	5.04
Clustering coeff.	0.43	0.29	0.38
Network diameter	6	4	6
Average hopcount	2.44	2.2	2.9
Node betweenness (max/min/avg)	144/28/72	76/2/36.8	302/2/269.9
Link betweenness (max/min/avg)	72/2/12.6	31/1/10.5	140/1/14.9

tributed to this topology's lower average hop count, network diameter, clustering coefficient, and higher average degree. The synthetic topology 1 also has six more links compared to the other two topologies: 74 vs. 68. On the other hand, the link attack on highest betweenness link for synthetic topology 2 results in a PDR drop to 60%. Visual inspection of synthetic topology 2 (Fig. 4c) clearly identifies the link failure between the central and west US is the cause of this since the network partitions. We can also infer the same conclusion by examining the link betweenness of synthetic topology 2 in Table 2, in which this link has 140 shortest paths.

The performance of sample topologies against malicious and non-malicious node perturbations is shown in Fig. 6. We evaluate the PDR during node failures for three cases: 10 random node failures, attack of the 10 highest ranked nodes based on betweenness, and attack of the 10 highest ranked nodes based on degree of connectivity. Figures 6a, 6b, and 6c show that node failures are worse than link attacks or failures (compared to Fig. 5), since each node failure is the equivalent of the failure of all links incident to that node. Our results indicate that attacks launched with knowledge of the network topology can cause the most severe degradation. We can also infer the tradeoff between robustness and the cost of building topologies using our framework. It should be noted that KU-LoCGen performs topology generation under cost constraints of a fixed and variable cost of each link, and thus we can compare the resilience of various cost points, with increasing cost providing increasing resilience due to better network connectivity when there are more links.

The performance evaluation of sample networks with varying failure probabilities is shown in Fig. 7 and Fig. 8. We averaged 100 simulation runs for the probabilistic failure scenarios. The seed to the random number generator is generated via the system clock, therefore we used a different seed for each run. The random variables used in the simulations were uniformly distributed. In these scenarios, PDR is calculated when the network elements are in the down state.
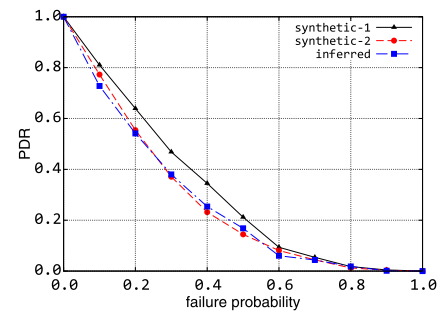
Fig. 7 Statistical node failure PDR
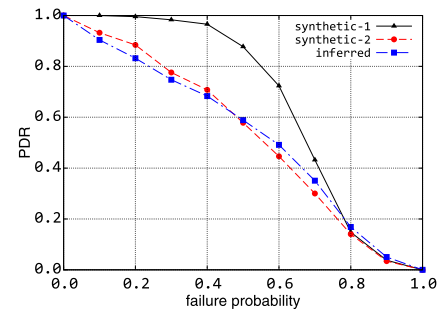

Fig. 8 Statistical link failure PDR

The state transition for each element occurs if the probability of failure of a network element is greater than the specified value p_r provided in the challenge specification file.

The performance of the sample networks with increasing probabilistic node failure is shown in Fig. 7. The PDR value varies between 100% and 0% as the node failure probability increases from 0% to 100%. The curves are close to each other since each sample topology has the same number of nodes, and failure probabilities are uniformly distributed. In particular, the synthetic 2 topology and Sprint inferred topologies show similar characteristics since the average degree values of those topologies are the same as listed in Table 2.

Figure 8 shows the PDR during the probabilistic link failures for synthetic 1, synthetic 2, and Sprint inferred topologies respectively. While the performance of the Sprint inferred and synthetic 2 topologies are close to each other, synthetic 1 topology has better performance for the probabilistic link failure scenario since it has more links compared to the other two topologies. Compared to the probabilistic node failures, probabilistic link failures do not impact the networks as much, since the impact of a node failure includes one or more links being brought down.

5.2 Area-based challenges

As previously discussed, our framework uses circles or polygons to model geographically correlated failures representative of large-scale disasters needed to evaluate network
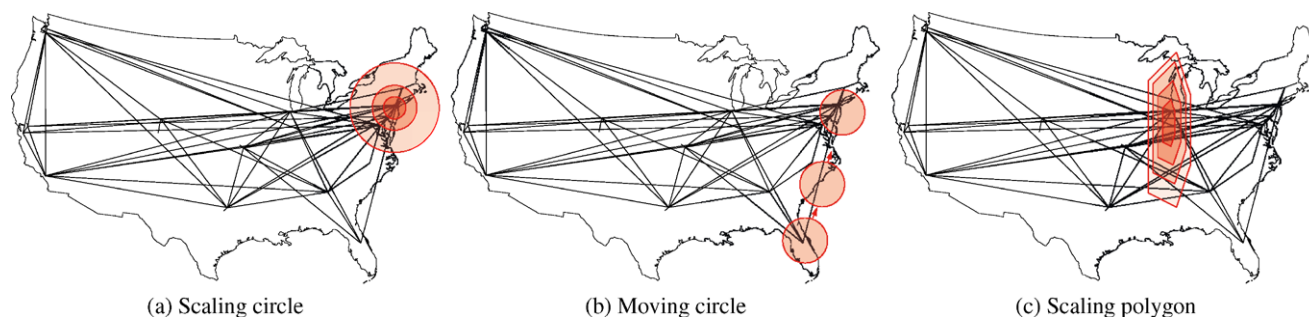
Fig. 9 Area-based challenge scenarios for Sprint logical topology
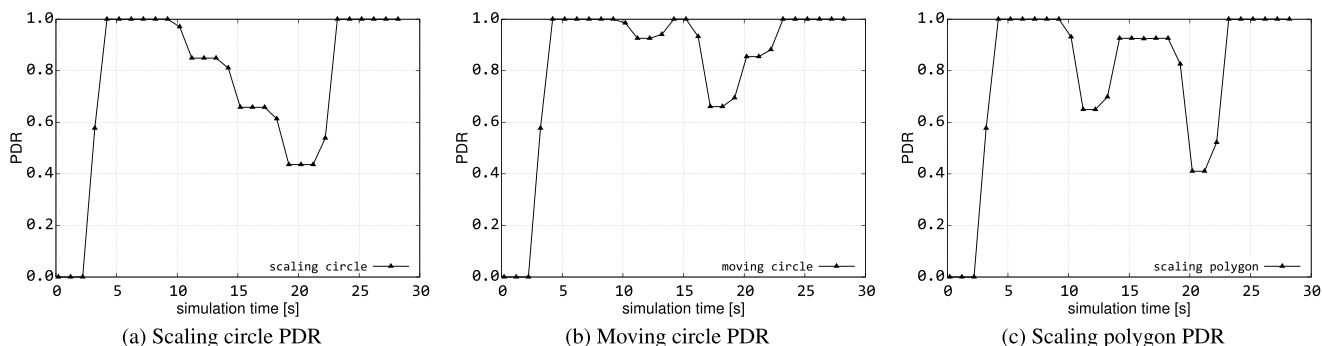
Fig. 10 Area-based challenge PDR for Sprint logical topology

survivability [30, 81]. Area-based challenges in our model can be stationary or evolving in time. Next, we present the results of three scenarios that demonstrate area-based challenges that evolve spatially and temporally. In all scenarios, as shown in Fig. 9, we use the Rocketfuel-based Sprint logical topology as shown in Fig. 4a. Application traffic is generated from 2 to 29 s and challenge scenarios were applied from 10 until 22 s for the performance plots shown in Fig. 10.

5.2.1 Scaling circle

To demonstrate a scaling circle area-based challenge scenario, we simulate a circle centered at $(-74.00°, 40.71°)$, in New York City (NYC) as shown in Fig. 9a, with a radius of $1°$ (approximately 111 km). We choose the scenario to be representative of an electromagnetic pulse (EMP) attack [2]. The PDR is shown in Fig. 10a. We choose the simulation parameters such that the radius doubles in every 4 s. As can be seen, the PDR reduces as the circular area doubles. The PDR drop depends on how many nodes and links resides in the circle for each step.

5.2.2 Moving circle

Next, we demonstrate an area-based scenario that can evolve spatially and temporally, such as to model a hurricane.

We simulate a moving circle in a trajectory from Orlando $(-81.37°, 28.53°)$ to NYC $(-74.00°, 40.71°)$. Three snapshots of the evolving challenge are shown in Fig. 9b. The radius of the circle is kept at $2°$ (approximately 222 km). We choose the simulation parameters for illustration such that the circle reaches NYC in seven seconds (sped up to constrain simulation time), with route recomputation every 3 s.

As shown in Fig. 10b, PDR reduces to 93% as the challenge starts only covering the node in Orlando at 10 s. As the challenge moves towards NYC in its trajectory, the PDR reaches one at 13 s. In this case, the challenge area includes only the link between Orlando and NYC, but since there are multiple paths, a single link failure does not affect the PDR, showing that *diversity for survivability* is crucial [75, 80]. As the challenge moves into the northeast US region at 16 s, the PDR drops to 66% as the challenge covers several nodes and links. The simulation shows that as the circle moves out of the more crowded region of the network, the PDR improves, until the challenge ends at 22 s.

5.2.3 Scaling polygon

Polygons are useful to model specific geographic challenges such as power failures that can cause large-scale network disruption as in the 2003 Northeast US blackout [26]. For a scaling polygon example, we show a 6-sided irregular poly-
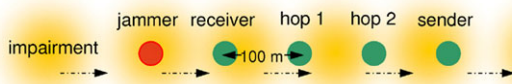
Fig. 11 Jammer and impairment combined scenario

Fig. 12 Wireless challenge scenario PDR

gon in the Midwest region of the US, roughly representative of the North American Electric Reliability Corporation (NERC) Midwest region [2], with vertices at: [($-87.91°$, $43.04°$), ($-89.09°$, $42.27°$), ($-89.64°$, $39.8°$), ($-88.54°$, $39.12°$), ($-88.24°$, $40.12°$), ($-87.65°$, $41.85°$)] as shown in Fig. 9c.

The PDR throughout the simulation is shown in Fig. 10c. In this scenario, the edges of the irregular polygon increase 1.8 times every 3 s. At 10 s the challenge affects 16 links, which causes the PDR to drop to 65%. The PDR then increases to 93%, even though more links and nodes are affected at 13 s because of route reconvergence. As the polygon increases in size, the PDR drops to as low as 41%, because the challenge area partitions the network at 21 s. This type of scenario can be used either to understand the relationship between the area of a challenge and network performability, or to model a temporally evolving challenge, such as a cascading power failure that increases in scope over time.

5.3 Wireless domain challenges

Wireless challenges are modelled as jammers and impairments in our ns-3 framework as discussed in Sect. 3. In this section, we present an example scenario that combines both types of challenges. In this scenario, a jammer node and impairment move as shown in Fig. 11. The sender is located at logical coordinate $(300, 0)$, the receiver is located at $(0, 0)$, and the jammer node is located at $(-100, 0)$. During the simulation the impairment sweeps across the wireless network from left to right horizontally.

The performance result of the above scenario is shown in Fig. 12. In this scenario, the jammer is set up so that it will cause 70% packet loss for the legitimate traffic between the sender and the receiver. As the impairment sweeps horizontally, the PDR changes accordingly. In the region where the impairment affects the jammer node, 100% PDR is achieved between the sender and the receiver. As the impairment affects the receiver or sender, the PDR drops to 0%.

It should be noted that for the wireless domain challenges, a jammer's mobility pattern can cause either random or targeted attacks, depending on intentional placement near a critical node vs. a jammer with a random mobility pattern.
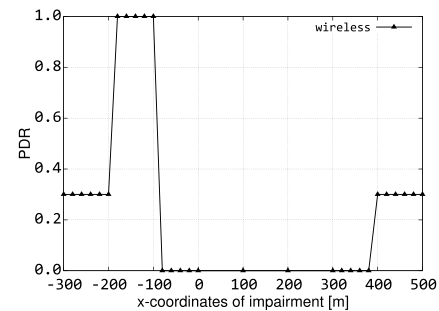
5.4 Simulation performance

As mentioned in Sect. 3, we utilised the ns-3 discrete-event simulator. Simulations that required single run were executed on a Linux based Ubuntu 9.10 computer that has a dual 1.66 GHz CPU and 1 GB RAM memory, which takes about 197 s of wall clock time to complete a single run. Execution of post processing scripts that are developed in the Perl language also takes another 166 s to strip the useful data out of the ns-3 trace files. We performed 100 run simulations on a machine with dual Intel Xeon 2.27 GHz quad-core processors with 72 GB of RAM running Linux CentOS 5.5. Each batch of 100 simulation runs, including the post-processing, took approximately 3–3.5 hours of wall clock time to complete. It should be noted that changing the packet rate and the size of topologies affects the time to complete the discrete-event simulations.

6 Impact of challenges on physical topologies

Network performance analysis under a variety of challenges is possible with this framework. We showed results of how this framework can be used on a layer 3 logical topology in Sect. 5. In this section we investigate the network performance of a *physical layer* topology. We use the Sprint fiber-optic map shown in Fig. 13[1] [43]. The map has no designation for fiber-optic nodes, instead the routes cross US cities. We project the cities to be physical node locations and connect them based on the map, which is sufficiently accurate for a national-scale map. The resulting physical topology shown in Fig. 13 has 245 nodes and 287 links.

A fiber-optic topology does not necessarily use all nodes to be traffic sources and sinks. There can be signal regenerators, cross-connects, and ADMs. Therefore, to realistically place source and sink points we utilised the Sprint global MPLS map [6], with a total of 115 MPLS PoPs in the US. Among these 115 PoPs, 83 exactly match to the physical topology we constructed. 7 more PoP locations closely

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[1]Other papers [17, 40] have used this 1999 map.

match to a city on the physical topology. For example the fiber-optic route map has a point in Coeur d'Alene, Idaho, while the MPLS map has a PoP located in Post Falls, Idaho, which are very close to each other, so we consider the Coeur d'Alene node on the physical topology adjacency matrix a traffic source and sink point. 25 PoP locations did not match to the physical topology well. For example the MPLS PoP in Springfield, Missouri does not lie on any Sprint fiber routes. These MPLS PoPs are backhauled over other service providers, and are thus excluded from our Sprint traffic matrix. The resulting traffic matrix has 90 source/sink pairs. The Sprint fiber-optic routes with Sprint MPLS PoP locations are shown in Fig. 14.

6.1 Challenge simulations on physical topologies

The physical topology has 245 cities of which 90 MPLS PoP locations match to the cities on the physical topology. Since not all cities are traffic source or sinks, the statistical failure scenarios would not be useful determining the performability of the network. Hence, we focus on simulating area-based challenges against the physical topologies representing large-scale disasters. We run the same area-based
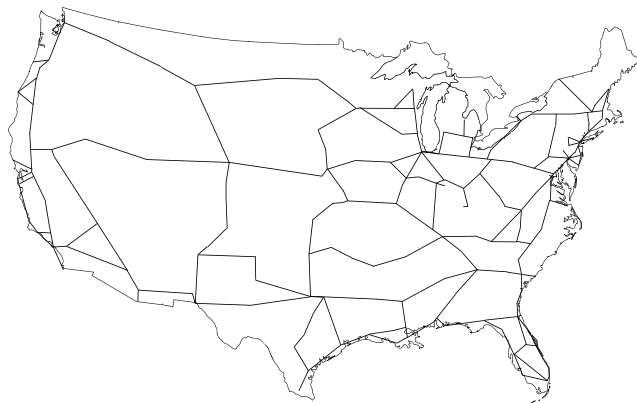
Fig. 13 Sprint fiber-optic routes
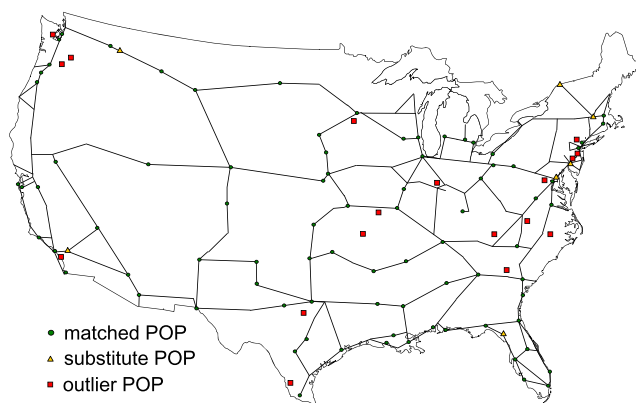
Fig. 14 Sprint MPLS PoP locations

scenarios on the physical topology that we ran on the Sprint logical topology (Sect. 5.2) as depicted in Fig. 15.

The performance of the physical topology is shown Fig. 16. The characteristics of the performance curves closely match between physical and logical topologies for the same area-based challenge scenarios. The difference is the PDR values. This is expected since the number of traffic sources and the sinks differ between each topology. We also increase the link bandwidth from 10 Mb/s to 100 Mb/s to prevent artificial drop of packets in the physical topology scenarios, since the maximum link betweenness in the physical topology is 8012 and the maximum link betweenness on the Sprint logical topology is 72.

Next, we demonstrate an area-based scenario representative of a hurricane hitting south central US as shown in Fig. 17. In the smallest area are the nodes in New Orleans and Biloxi of which only the New Orleans node is a MPLS PoP node. In the second circular area challenge, the nodes are: New Orleans, Baton Rouge, Lafayette, Biloxi, and Mobile, in which 4 out of the 5 affected nodes are PoP nodes. In the largest affected area there are a total of 10 nodes, 6 of which are the PoP nodes. However, none of the three circular challenge areas cover any logical links or nodes on the map in Fig. 4a, permitting us to investigate the differences between logical and physical topologies.

The network performance of physical and logical topologies when the south central US region is challenged is shown in Fig. 18. Since there are no nodes or links in the logical topology impacted, the PDR appears to be 100%. On the other hand, the PDR of the physical topology drops to 98%, 91%, and 86%, respectively, as the challenge area covers more nodes and links. This demonstrates that it is imperative to study the impact of area-based challenges on the *physical* topologies. Traditional layer-3 logical topologies are insufficient to understand the impact of physical challenges against the network infrastructure.

7 Discussion

Network challenges are inherent in the communication environment. While they are inevitable [80], a thorough understanding of the consequences can help us implement proper mitigation techniques.

7.1 Network challenges

Networks face challenges that are inherent in the environment and the consequences of these challenges can be costly. The resulting impact of these challenges is related to the probability of occurrence, the magnitude of a challenge, and the duration of a challenge. In this work we study the temporal and spatial characteristics of network challenges. Even if
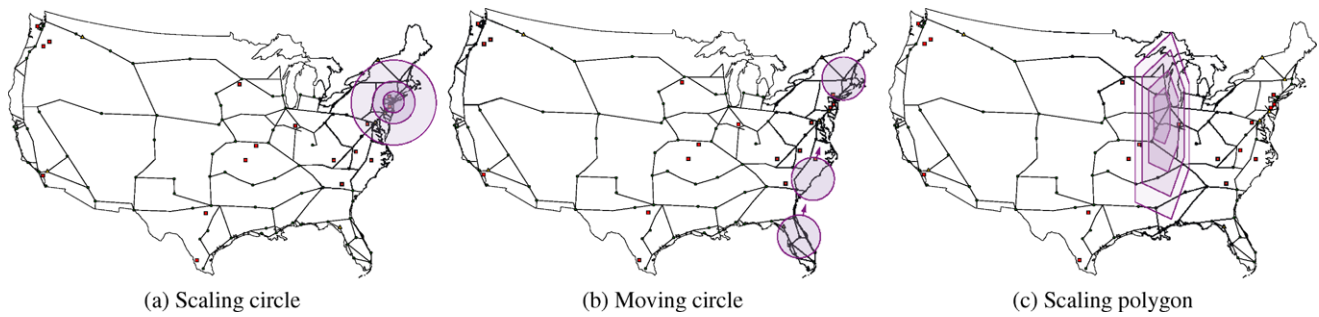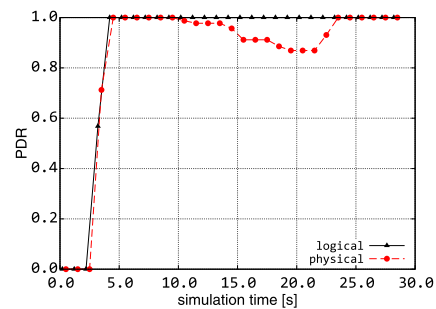
Fig. 15 Area-based challenge scenarios for Sprint physical topology
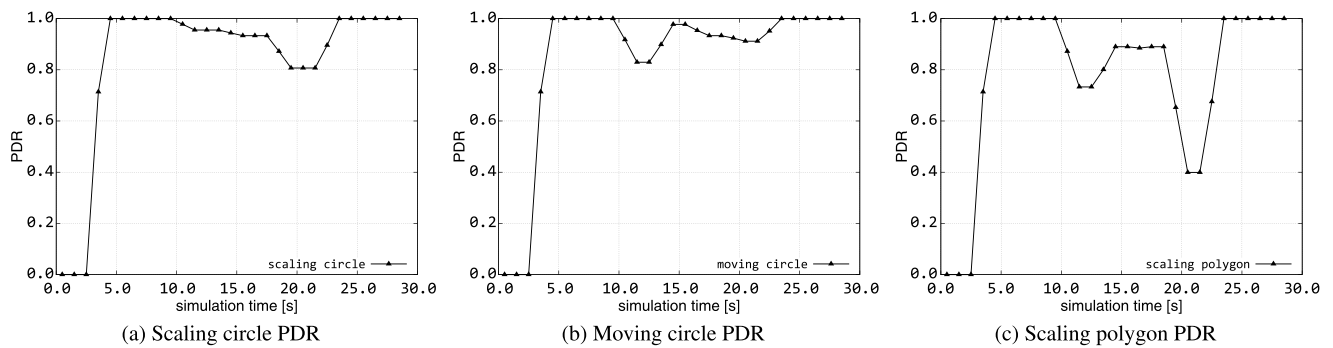
Fig. 16 Area-based challenge PDR for Sprint physical topology
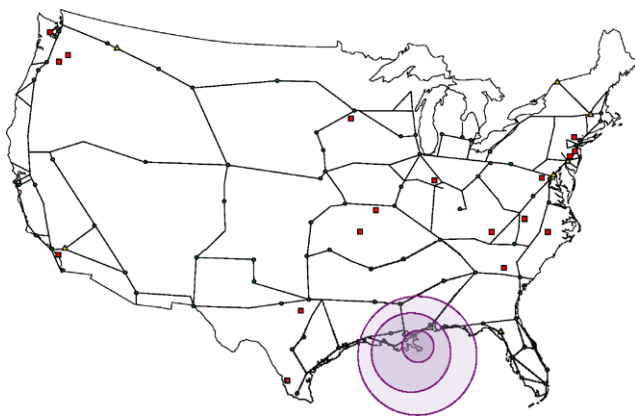
Fig. 17 South central area-based challenge scenario

Fig. 18 South central US challenge PDR

a challenge is an act of nature, statistical recording of such challenges can provide for the allocation of resources at the right time to reduce the impact of the challenges. Another factor contributing the probability of occurrence is social behaviour: malicious attacks [37, 89] affect the severity of the consequences. The magnitude of a challenge can be characterised by the following:

- challenge area
- number of impacted nodes and links in challenge area
- significance of network elements in the challenge area

- traffic carried through the affected area

As seen in our simulation results, magnitude of a challenge impacts the result of challenges. Finally, the duration of a challenge is critical factor impacting the network performance. This is related to the ATIS/ANSI (unservability, duration, extent) triple [80, 86]. Natural or human-made disasters causing power outages increase the network downtime [71, 87]. Our framework could provide valuable insight for probable consequences of network failures during the varying challenge duration. Understanding the characteristics of challenges can provide insight into the mitigation strategies to cope with various challenges.

7.2 Mitigation against network challenges

As our simulation results show, the consequence of a network challenge is degraded network state that may lead to a service impairment [77, 78, 80]. Since challenges exist in the communication environment inherently, we cannot avoid them, but we can mitigate the impact. So, the question to be answered is: *How to mitigate the impact of challenges?* The *enablers* for designing resilient networks are given in the ResiliNets architecture [79, 80]. These enablers such as self-protection, connectivity, redundancy, diversity, and multi-level design can improve the service level of the networks, thus providing more resilient networks. Self-protection and security is necessary for the first-line of defence against attackers. Wireless networks face challenges that are inherent in the environment and DTN architectures can permit communication even when stable end-to-end paths do not exist. Redundancy can improve the service level against random failures. Spatial diversity of links between nodes resists against geographically correlated failures. Designing communication protocols and network architectures independently to improve resiliency provides multi-level aspects of resilient network design. However, these resilient network design enablers come at the cost and complexity of building these hardened systems. For example, adding new links for diverse paths or nodes for redundancy increases the total cost of the network. The challenge framework presented in this paper can be useful for design, implementation, and verification of these architectural enablers to understand how to optimally deploy components for the greatest resilience/cost ratio. This framework can also provide insight to the trade-offs of design choices.

The enablers for resilient network design are one aspect of the problem. From a policy perspective, lack of outage data hinders determining where the focus should be when designing systems. In spite of the existence of some studies that cover factors affecting the global Internet [50, 53, 65, 67], there is not a comprehensive study identifying the ratio of elements that contribute to the service failures in the Internet. This can be attributed to service providers' unwillingness to share outage information due to security and competitive reasons. An *open* database similar to the US FCC (Federal Communications Commission) NORS (Network Outage Reporting System) [63] for sharing outage information would benefit the research community toward increasing the resilience of the Internet.

Lastly, the human factor affects the service levels of the Internet. Approximately 50% of the PSTN failures are attributed to human related causes [45]. The situation is not any better for Internet services [34, 57, 65] due to misconfiguration errors caused by humans. One solution to the problem is to design better human–machine interfaces and training programs [9]. Additionally, recommended best practices can help that encompass human, management, and policy aspects for the management of telecommunication services [41].

7.3 Remediation after network challenges

Networks are designed based on limited resources, therefore building 100% resilient networks is not possible. The ResiliNets enablers summarised above provide guidance on *defensive* measures against network challenges. However, when networks are impacted by challenges, the enablers may be insufficient to provide the necessary service with the defenses penetrated. Therefore the effects of the challenge should be *remediated*. It should be noted that there is inconsistency in the terminology used by the community. We define remediation as to mitigate the effects of the adverse event or condition. *Recovery* involves bringing the operations to the original state [52, 78, 80].

This is an active area of research. Recently, *IEEE Communications Magazine* dedicated the January 2011 issue to network recovery [44, 54, 56, 64, 74]. Network recovery involves planning and preparedness, proper emergency communication, and management during a disaster.

8 Conclusions and future work

Recognising the challenges faced by networks is crucial for understanding network behaviour. We described how they can be categorised and presented a comprehensive framework to evaluate network performance when faced by realistic stationary or evolving challenges. This framework separates network topology from challenge specification, which increases tractability and flexibility. We demonstrated that while logical topologies are appropriate for statistical challenge scenarios or analysing network-level attacks, physical topologies are necessary to realistically study geographically correlated failures. Our results indicate that network performance varies depending on the type and severity of the challenge applied.

This paper has concentrated on illustrating the basic functionality of our challenge framework to demonstrate its utility in understanding network resilience. Future work will consist of applying this framework to a variety of real and synthetic wired, wireless, and mixed topologies to better understand the resilience of existing and future networks. Furthermore, we will begin to apply this methodology to a large-scale with emulated challenges, using the GpENI (Great Plains Environment for Network Innovation) [82, 83] testbed.
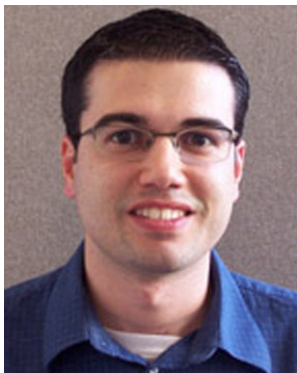
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