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TECHNICAL REPORT

Designing Networks that are Capable of Self-Healing and Adapting

April 2017

HDTRA1-11-1-0048

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14. ABSTRACT
Using tools from statistical mechanics, combinatorics, boolean networks, and numerical simulations, and inspired by design principles from biological networks, we will undertake the following objectives: Quantify the effects of local damage and develop strategies for absorbing it, develop topological design principles for self-healing networks, and applications, and construct an all-possible-paths model for network adaptation.

15. SUBJECT TERMS
Networks, self-healing, topological, adaptation

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (°F)	$[T(^{o}F) - 32]/1.8$		degree Celsius (°C)
degree Fahrenheit (°F)	$[T(^{o}F) + 459.67]/1.8$		kelvin (K)
Radiation			
curie (Ci) [activity of radionuclides]	3.7	$\times 10^{10}$	per second (s^{-1}) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
rad [absorbed dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [gray (Gy)]
rem [equivalent and effective dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [sievert (Sv)]

*Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

†Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

FINAL REPORT: DESIGNING NETWORKS THAT ARE CAPABLE OF SELF-HEALING AND ADAPTING

1 COVER SHEET

PI/CO-IS

Name	*Role*	*Location*
Thomas Fink	PI	LIMS, UK/CNRS, France
Guido Caldarelli	CO-I	LIMS, UK/Lucca, Italy
John Harer	CO-I	Duke, USA

INSTITUTE (OF PI)

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GRANT NUMBER

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2 OBJECTIVES

Using tools from statistical mechanics, combinatorics, boolean networks, and numerical simulations, and inspired by design principles from biological networks, we will undertake the following objectives:

1. Quantify the effects of local damage and develop strategies for absorbing it.
2. Develop topological design principles for self-healing networks, and applications.
3. Construct an all-possible-paths model for network adaptation.

3 APPROACH

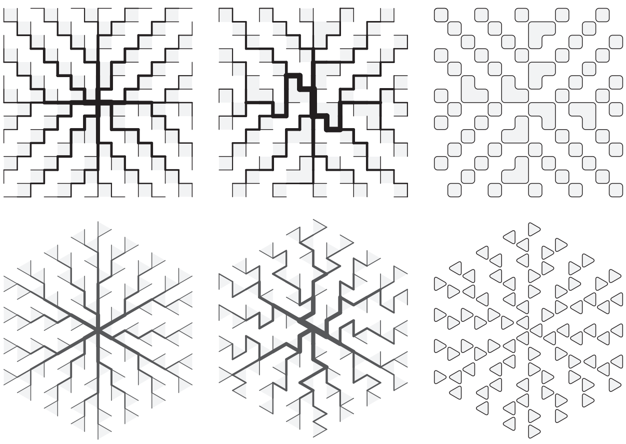
1. *Quantify the effects of local damage and develop strategies for absorbing it.* We shall begin by exploring different ways to compensate for the loss of one or more edges and investigate the way that various invariants change under this stress. We plan a search for critical phenomena with respect to damage for weighted networks, and will do an exhaustive study of the effect of edge loss on network motifs (weighted and boolean). We shall then move to the construction of "primitives", topologically minimal networks for achieving a given dynamical task, which are most vulnerable to damage, and investigate how other networks differ from these. Finally, using analytics, we will look for principles that characterize how to absorb damage.

2. *Develop topological design principles for self-healing networks, and applications.* In the second year of the project we shall go beyond examinations of network behaviors into the world of making predictions. We shall extract topological design trends that enable us to determine which edges are likely to be most disruptive, and design against them. For boolean networks essential properties of the dynamics should be useful in characterizing network operation and vulnerability. We shall explore the relationship between our models and topological characterizations known to possess good network resilience (fractal and expander graphs). And we shall begin the study of real infrastructure networks by applying Laplacian minimization to the London Underground.

3. *Construct an all-possible-paths model for network adaptation.* We shall begin this objective by writing a simulation to study our all-possible-paths model of network adaptation. With this simulation we shall consider different numbers of nodes and different geometries. We shall explore the parameter space of our simulations, tracking the magnitude of resistance changes and degrade/inhibit current constants. An exploration of the trade-off between self-healing and adaptation will be critical, and we shall investigate this trade-off when the network nodes are changing so fast that the network never has time to equilibrate.

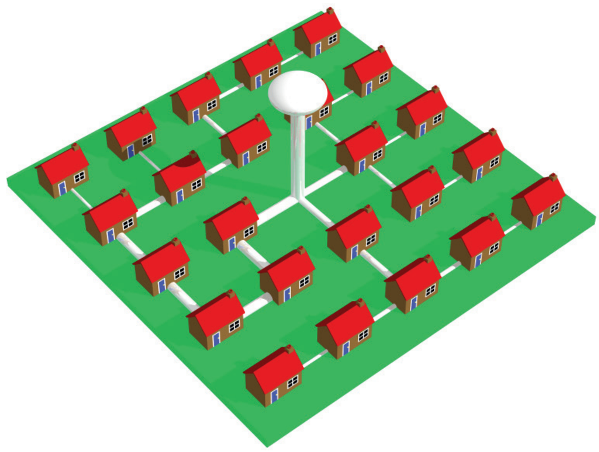
EASILY REPAIRABLE NETWORKS

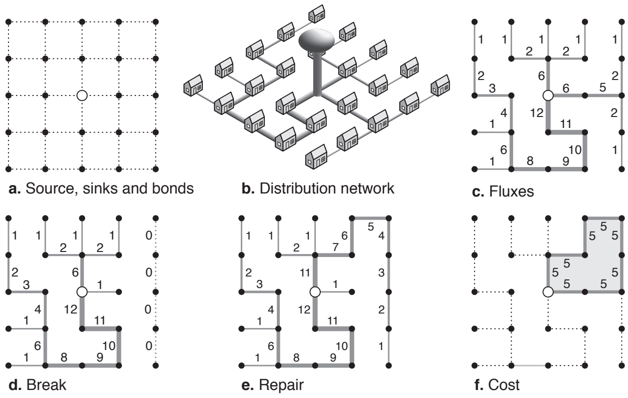
There are two strategies for coping with network damage or attacks: robustness and repairability. Whereas robust networks are resilient to errors due to internal redundancy, in leaner repairable networks, function is restored through external intervention. We introduce a model of distribution networks, in which a commodity is transported from a single source to many recipients, and study the process of damage and repair. We show that easily repairable networks have exactly three levels of hierarchy: terminal hairs which branch off of secondary arms which branch off of primary arms which are connected to the source. This is in contrast to robust networks, which tend to have many levels of hierarchy. We find that the expected cost of repair is proportional to the square root of the number of recipients. This suggests that repairability can be a viable alternative to robustness for maintaining network function. This work may have wide applications on natural resource distribution across countries, supply distribution in the battlefield, and utility infrastructure in cities.



a. Original network **b.** After many breaks **c.** Independent dormant loops

Networks that are easy to repair after many breaks. The original networks (left), the networks after many break- repair cycles (center), and the independent dormant loops.

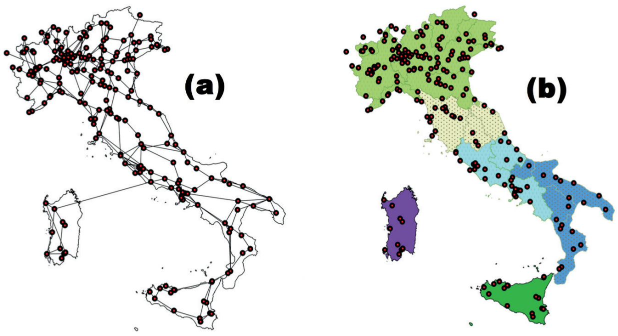




A distribution network, and the process of damage and repair. b. Each house requires one unit of water per day from a tower. The flux into each house is equal to the number of houses downstream from it, plus one. Each day a random pipe breaks, and a new pipe must be built elsewhere to reconnect the cut off houses. Moreover, some pipes upstream and down from the new pipe must be resized to accommodate the change in demand. What network minimizes the expected total change in flux, or pipe altered, per break? a. The source (open circle), nodes (closed circles) and bonds, which are pos- sible edges (dashed lines). b. The tree of edges connecting the nodes to the source. c. The fluxes J_i at each edge. d. An edge is broken, splitting the tree in two. e. A new bond is made an edge, reconnecting the subtrees, and the updated fluxes J'_i . f. The changes in fluxes $|J'_i - J_i|$. They vanish everywhere except on the loop through the broken and repairing edges. The cost of repair is the flux through the broken edge times the remaining loop length: $c = 5 \cdot (8-1) = 35$.

GREEN POWER GRIDS

The increasing attention to environmental issues is forcing the implementation of novel energy models based on renewable sources, fundamentally changing the configuration of energy management and introducing new criticalities that are only partly understood. In particular, renewable energies introduce fluctuations causing an increased request of conventional energy sources oriented to balance energy requests on short notices. In order to develop an effective usage of low-carbon sources, such fluctuations must be understood and tamed. In this paper we present a microscopic model for the description and the forecast of short time fluctuations related to renewable sources and to their effects on the electricity market. To account for the inter-dependencies among the energy market and the physical power dispatch network, we use a statistical mechanics approach to sample stochastic perturbations on the power system and an agent based approach for the prediction of the market players' behavior. Our model is a data-driven; it builds on one day ahead real market transactions to train agents' behaviour and allows to infer the market share of different energy sources. We benchmark our approach on the Italian market finding a good accordance with real data.



Input elements for evaluating the size of the balancing market (i.e. the short time fluctuations in power generation/demand). In panel (a) we show the electric transmission network in Italy; the topology and the physical characteristics of lines and generators are the constraints that influence the power flow. In panel (b) we show the market zone splitting used for managing the congestions of the entire Italian network.

SELF-HEALING NETWORKS

We introduce the concept of self-healing in the field of complex networks. Obvious applications range from infrastructural to technological networks. By exploiting the presence of redundant links in recovering the connectivity of the system, we introduce self-healing capabilities through the application of distributed communication protocols, thereby conferring "smartness" on the system. We analyze the interplay between redundancies and smart reconfiguration protocols in improving the resilience of networked infrastructures to multiple failures. In particular, we measure the fraction of nodes still served for increasing levels of network damages. We study the effects of different connectivity patterns (planar square-grids, small-world, and scale-free networks) on the healing performances. The study of small-world topologies shows us that the introduction of some long-range connections in the planar grids greatly enhances the resilience to multiple failures, giving results comparable to the most resilient (but less realistic) scale-free structures.

5 PERSONNEL SUPPORTED

Position	*Name*	*Subject*	*Location*	*Notes*
Undergraduate	Marec Serlin	Physics	LIMS	Summer Undergrad. Res. Fellowship, visiting from Caltech.
Undergraduate	Eugene Park	Math	Duke	Models of self-healing networks (undergrad. senior thesis).
Graduate student	Anastasia Deckard	Math	Duke	3rd/4th year PhD. Wrote software for simulation.
Undergraduate	Nick Day	Math	LIMS	Summer project at LIMS, exact dynamics of small networks.
Postdoc	Vincenzo de Leo	Physics	LIMS	
Postdoc	W. Quattrociocchi	Physics	LIMS	PhD from Siena.
Postdoc	Jamie Blundell	Physics	LIMS	PhD from Cambridge. Analytics of network dynamics.
Postdoc	Leonardo Briganti	Physics	LIMS	
Postdoc	Alexis Gallagher	Physics	LIMS	PhD from Oxford. Adaptation/evolution code, model.
Postdoc	Kedron Silsbee	Physics	LIMS	BS from Caltech. Simulation, analytics of network dynamics.
Collaborator	Robert Farr	Physics	LIMS/Unilever	Working on easily repairable networks.
Collaborator	Michael Shapiro	Bimedicine	Duke/Tufts	Tufts Immunology Program. Co-developed evolutionary framework for network models of resource distribution.

6 PUBLICATIONS

All publications have been accepted by, or have been submitted to, peer-reviewed journals.

Easily repairable networks	R Farr, J Harer, T Fink	Phys. Rev. Lett., **113**, 13	2013
Self-healing networks: redundancy and structure	W. Quattrociocchi, G. Caldarelli, A. Scala	arxiv.org/abs/1305.3450	2013
Bootstrapping topological properties and systemic risk of complex networks…	N. Musmeci et al.	J. Stat. Phys. 151, 720	2013
Snowflake-Shaped Networks Are Easiest To Mend	R Farr, J Harer, T Fink	*New Scientist, Slashdot*	2014
Distributed generation and resilience in power grids	A. Scala et al.	sub. to CRITIS	2013
Failure filtrations for fenced sensor networks	E. Munch, M. Shapiro, J. Harer	Intl J. Robotics Res. 31, 9	2012
Complex weighted networks as randomly reinforced urn process	G. Caldarelli et al.	Phys. Rev. E 87, 020106	2013
Progress in the physics of complex networks	G. Caldarelli, G. Kanadiakis, A. Scarfone	Euro. Physical J. B 212, 1	2012
Robustness & assortativity…in scale-free networks	G. D'Agostino, A. Scala, V. Zlatić, G. Caldarelli	EPL 97, 68006	2012
Robustness and adaptability of small network dynamics*	T. Fink et al.	sub. to Phys. Rev. E	2012
Networks with arbitrary edges multiplicities	V. Zlatić, D. Garlaschelli, G. Caldarelli	EPL 97, 28005	2012
Green power grids	M. Mureddu, G. Caldarelli et al.	arxiv.org/pdf/1503.02957	2014
Coupling news sentiment with web browsing data predicts intra-day stock prices	G. Ranco, I. Bordino, et al.	arxiv.org/abs/1412.3948	2014

7 INTERACTIONS/TRANSITIONS

SELECTED MEETINGS, CONFERENCES, SEMINARS

2012
DARPA 'Biochronicity' program annual meeting, Seattle, WA, August 2012.
DTRA Basic Research Technical Review, D.C., July 2012.
T Fink/J Harer, DARPA 'Biochronicity' program annual meeting, Seattle, WA, August 2012.
G Caldarelli, NETSCI 2012 Evanston June 20th 2012. DebtRank: too central to fail?
T Fink, J Harer and C Caldarelli gave, between them, 6 invited seminars.

2013
Fink gave invited seminars at the physics departments in Leeds and Oxford.
J Harer participated in a program on high-dimensional data at SAMSI in 2013.
DTRA Basic Research Technical Review, D.C., July 2013.

2014
Caldarelli was the chief organizer of the European Conference on Complex Systems, held in Lucca, Italy.
Fink have an invited seminar to the Oxford Theoretical Physics department: "Repairability as an alternative to robustness".
T Fink, J Harer and C Caldarelli gave, between them, 4 other invited seminars.

OTHER LABORATORIES OR DOD AGENCIES

Fink is Co-Pi, and Harer PI, in the DARPA program 'Biochronicity' (program manager: Christian Macedonia). Part of this program focuses on the robustness and adaptability of network dynamics.

Harer is PI, and Fink is Co-Pi, in the DARPA program 'Biochronicity: Time, Evolution, Networks, and Function' (program manager: C. Macedonia). Part of this program focuses on robustness of networks, which compliments our DTRA work on healing and repairability.

Harer will be faculty in residence at SAMSI (Statistical and Applied Mathematical Sciences Institute) in 2013/14.

TRANSITIONS

Caldarelli received a new grant from EU FP7: Financial systems simulation and policy modelling (SIMPOL).

Fink has been made a consultant to Boston Consulting Group (BCG) to study adaptive strategy and the network of interconnectivities in companies. BCG is also interested in the work funded by our DTRA grant.

Fink received a new grant from Boston Consulting Group (BCG) to study robustness and adaptability of human enterprise, such as companies or regiments. Our DTRA work on repairability has fed back into this.

Fink received a new grant from EU FP7: GROWTHCOM. This will extend our DTRA work on repairability.

8 INVENTIONS, PATENT DISCLOSURES

N/A.

9 HONORS, DEGREES, AWARDS

Guido Caldarelli was made full Professor at the University of Lucca (he has a joint position at LIMS and Lucca).

10 WMD COURSES TAUGHT

Harer gave a talk on this DTRA grant to undergraduate math majors at Duke.

11 QUAD CHART

Uploaded to the DTRA Basic and Fundamental Research Community Portal.

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