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TECHNICAL REPORT

Spatiotemporal Response of Complex Multilayer Networks to WMD Attacks

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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 × 10 ⁻²	meter (m)
foot (ft)	3.048 × 10 ⁻¹	meter (m)
yard (yd)	9.144 × 10 ⁻¹	meter (m)
mile (mi, international)	1.609 344 × 10 ³	meter (m)
mile (nmi, nautical, U.S.)	1.852 × 10 ³	meter (m)
barn (b)	1 × 10 ⁻²⁸	square meter (m ²)
gallon (gal, U.S. liquid)	3.785 412 × 10 ⁻³	cubic meter (m ³)
cubic foot (ft ³)	2.831 685 × 10 ⁻²	cubic meter (m ³)
Mass/Density		
pound (lb)	4.535 924 × 10 ⁻¹	kilogram (kg)
unified atomic mass unit (amu)	1.660 539 × 10 ⁻²⁷	kilogram (kg)
pound-mass per cubic foot (lb ft ⁻³)	1.601 846 × 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 × 10 ⁻¹⁹	joule (J)
erg	1 × 10 ⁻⁷	joule (J)
kiloton (kt) (TNT equivalent)	4.184 × 10 ¹²	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350 × 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 × 10 ⁵	pascal (Pa)
pound force per square inch (psi)	6.984 757 × 10 ³	pascal (Pa)
Temperature		
degree Fahrenheit (°F)	[T(°F) - 32]/1.8	degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8	kelvin (K)
Radiation		
curie (Ci) [activity of radionuclides]	3.7 × 10 ¹⁰	per second (s ⁻¹) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760 × 10 ⁻⁴	coulomb per kilogram (C kg ⁻¹)
rad [absorbed dose]	1 × 10 ⁻²	joule per kilogram (J kg ⁻¹) [gray (Gy)]
rem [equivalent and effective dose]	1 × 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.

Appendix A: Accomplishments

By addressing accomplishments, specifically what was done and what was learned, allows DTRA to assess the progress has been made during the reporting period. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report".

In the Accomplishments Section, the PI must address the following five (5) questions:

1. What are the major goals of the project?

List the major goals and objectives of the project. In cases where the goals or objectives are different from the original plan or the previous reporting period, provide the updated goals and objectives and a discussion of the reason for the change.

Write your responses in here.

Understand the fundamentals of human mobility, to help us uncover the impact of a WMD attack on the population. Develop analytical tools to study the controllability of an arbitrary complex directed network. Identify the minimum set of driver nodes to control the whole network. Study which network characteristics determine the controllability.

Examine the efficiency and stability of ranked results returned by various ranking methods, such as Google's pagerank. Based on numerical results, identify main topological network features affecting ranking stability. Develop an analytical approach to quantify the stability of ranked results (or lack thereof) and provide guidelines for improvement.

2. What was accomplished under these goals?

For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive and negative); and 4) key outcomes or other achievements.

Write your responses in here.

Write your response in here.

Human Mobility

Some of our early work on this grant pertained to human mobility, resulting in a number of fundamental discoveries, reported in several Nature and Science publications, with several key findings:

- 1) A range of applications, from predicting the spread of human and electronic viruses to city planning and resource management in mobile communications, depend on our ability to foresee the whereabouts and mobility of individuals. Also, for DTRA the need to understand the impact of a WMD of physical, chemical or biological nature, requires us to know where people are and how they move around. This raises a fundamental question: To what degree is human behavior and mobility predictable?

- 2) We explored the limits of predictability in human dynamics by studying the mobility patterns of anonymized mobile phone users.
- 3) We find a 93% potential predictability in user mobility across the whole user base. Despite the significant differences in the travel patterns, we find a remarkable lack of variability in predictability, which is largely independent of the distance users cover on a regular basis.

Network Controllability

- 1) We show that mapping the control of a complex system into structural control allows us to make progress even if the link weights are unknown. Using this tool, we can identify a set of driver nodes that can control the whole system, which is our first key result.
- 2) We find, rather surprisingly, that the number of driver nodes is determined mainly by the network's degree distribution, which is our second key result. It allows us to analytically calculate the number of driver nodes for networks with arbitrary degree distribution using the cavity method, developed in statistical mechanics.
- 3) Using a combination of analytical and numerical tools, we show that controllability is determined by two network characteristics: average degree and degree heterogeneity.
- 4) We show that controllability is rather robust to link failures, allowing us to map the robustness problem into percolation, and thus calculate its dependence on network parameters.
- 5) Finally, we apply these tools to a wide range of real networks, arriving to the unexpected conclusion that sparse and degree heterogeneous networks are the most difficult to control, which are exactly the characteristics that are found in many complex systems, from the cell to the Internet. We also show that in most real systems most links can be re-moved without affecting our ability to control the whole system.

Centralized vs distributed control (Nature Communications).

- 1) We introduced tools to identify the driver nodes, nodes through which we can achieve full control, predicting the existence of multiple control configurations. This prompted us to classify each node in a network based on their role in control.
- 2) A node is critical, intermittent or redundant if it acts as a driver node in all, some or none of the control configurations, respectively. We developed an analytical framework to identify the category of each node, leading to the discovery of two distinct control modes in complex systems: centralized versus distributed control.
- 3) We predicted the control mode for an arbitrary network and showed that one can alter it through small structural perturbations. The uncovered bimodality has implications from network security to organizational research and offers new insights into the dynamics and control of complex systems.

Rank Stability

- 1) We find that real networks with heavy-tailed degree distributions naturally lead to a set of super-stable nodes that have such a high number of "recommendations" (in-

degree) that their ranking becomes independent of who recommends them. This is somewhat unexpected from the perspective of the network architecture: the scale-free nature of these networks normally implies a lack of objective criteria to distinguish hubs from non-hubs. The balance of rank stability and fluctuations do allow us, however, to identify a few hubs that respond in a distinct fashion to perturbations.

- 2) Both our analytical predictions and numerical results indicate that the number of super-stable nodes is very small. As predicted by our scaling analysis, this number is largely unaffected by most network characteristics and only a significant increase in system size can increase their number.
- 3) We infer that across a large number of systems a small number of components (nodes) are bound to play a disproportionate role in the system. These nodes are often easy to identify: a simple link counting should place them at the top, limiting the usefulness of pagerank to ranking nodes that are not super-stable.
- 4) Our results suggest that the success of pagerank was the inadvertent consequence of the scale-free nature of the web graph. Had the web been an exponential network, the ranking provided by pagerank would have been unreliable given the incompleteness of the web graph. Indeed, in 1999 Google indexed only 7.8% of the web and even today its coverage is less than half of the indexable web. Yet, the scale-free property of the web graph leads to the emergence of a small number of super-stable nodes, for which, a simple count of the in-degree offers the correct relative ranking. As the www grew, the ranking stability at the top increased, making the top ranked nodes even easier to identify.
- 5) Counter-intuitively, we find that the growth of the web, instead of making search more difficult by offering more hits, helps select clear winners, offering better ranking clarity at the top.

3. What opportunities for training and professional development has the project provided?

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project.

"Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor.

"Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

Write your response in here.

Training: mentor a visiting graduate student: Marton Posfai (from Hungary).

Professional development: participation in the following conferences and workshops:

1. Workshop on Clusters and Patterns, January 11-13, 2011, Budapest, Hungary.
2. XVI International Symposium of Pneumology, Sevilla, Spain, February 4-5, 2011, "Network Medicine. The Future is HERE".
3. Complexity Conference: NICO and SONIC, March 6-7, 2011, Evanston, IL, "From the WWW to Network Science: why was Google's pagerank successful after all?"
4. Physics Days 2011, Sharing Methods, Exchanging Ideas, March 29-31, 2011, Helsinki, Finland, "Statistical mechanics of complex networks: from the topology of the WWW to the robustness of the cell".
5. Applications of Network Theory – the Conference, April 7-9, 2011, Stockholm, Sweden, "Controllability of complex networks".
6. Drug Response - A Tool for Understanding the Systems Biology of Type 2 Diabetes, April 21-22, 2011, Bethesda, Maryland, "Network medicine: from cellular networks to human diseases".
7. Hungarian Scientists in the US: Yesterday, Today and Tomorrow, April 25, 2011, Columbia University, New York, "Scale-free networks" (keynote).
8. FET 2011, The European Future Technologies Conference and Exhibition Science beyond Fiction, May 4-6, 2011, Budapest, Hungary, Topic: Integrating ICT, Complexity Science and the Social Sciences.
9. Symposium: Integrative Network Biology and Cancer Institute of Cancer Research (ICR), May 14-15, 2011, Chelsea, UK, "Network medicine: from the disease to comorbidity patterns".
10. Seoul Digital Forum 2011: Connected: Into a Shared Future, May 25-27, 2011, Seoul, Korea, "Network economics".
11. Physics and Biological Systems, June 14-17, 2011, Orsay, France, "Network medicine: from cellular networks to the human disease".
12. International Workshop on Coping with Crises in Complex Socio-Economic Systems (CCSS Workshop 2011), June 20-25, 2011, Zurich, Switzerland, "Collective response of human populations to large-scale emergencies" (keynote).
13. 9th [BC]2 Basel Computational Biology Conference Multiscale Modeling, June 23-24, 2011, Basel, Switzerland, "Network medicine: from cellular networks to the human disease" (keynote).
14. European Conference on Machine Learning and Principles and Practice in Knowledge Discovery in Databases, ECML PKDD 2011, September 5-9, 2011, Athens, Greece, "Human dynamics: From human mobility to predictability".
15. Germany, International Workshop and 2nd Baltic Autumn School in Systems Biology, September 7-9, 2011, Lubeck, "Network medicine: From the cellular network to the human disease".
16. International Workshop on Finding Patterns of Human Behaviors in Network and Mobility Data, Finding NEMO @ ECML-PKDD 2011, Friday, September 9, 2011, Pisa, Italy, "Human Dynamics: From Human Mobility to Predictability"
17. European Conference on Complex Systems (ECCS 11th Annual Meeting), September 12-16, 2011, Vienna, Austria, "Taming complexity: Controlling networks".

18. WIN: Workshop on Information in Networks, September 9-October 1, 2011, New York University, "Taming Complexity: Controlling networks".
19. Analysis of Mobile Phone Datasets and Networks, NetMob2011, October 10-11, 2011, MIT Media Lab, Cambridge MA, "Human Dynamics and Cell Phones: From mobility to predictability".
20. Networks Understanding Networks, October 12-13, 2011, MIT Media Lab, Cambridge MA, "Network Science: From the Web to the Cell".
21. 2011 Connected Health Symposium, October 20-21, 2011, Boston, Massachusetts, The Futurists, "Expert panel #10: The Futurists: A Fresh Look by Some Smart People at the Twists and Turns We Cannot Know ... But Need to Think About".
22. CI Speaker Series on Computational Knowledge Synthesis, University of Chicago, Computation Institute, October 24, 2011, Chicago, IL, 2011 "Taming Complexity: Controlling Networks".
23. DES⁴: Distinguished Engineering and Science Speaker Series, MIT's departments of CCE, MechE, Math, Biology, Physics, MITEL, October 26, 2011, Cambridge, MA, "From Network Science to Human Dynamics".
24. Workshop in Reflexivity and Social Change, Central European University, November 3-4, 2011, Budapest, Hungary.
25. Swiss Finance Institute, SFI Evening Seminar with Prof. Laszlo Barabási, November 9, 2011, Zurich, Switzerland, "Networks: Formation, Dynamics and Control".
26. Heinz von Foerster Congress, Self-Organization and Emergence, November 10-13, 2011, Vienna, Austria, Network Science: From the Web to the Cell."
27. International Brand Development Conference on the Wielkopolska Regional Brand, November 24, 2011, Poznan, Poland, "The Science of Networks".
28. FuturICT: FET Flagship Pilots Midterm Conference, November 24, 2011, Warsaw, Poland.
29. The Spanish Clinical Research Network, (CAIBER), 2011 Scientific Meeting, November 29, 2011, Madrid, Spain, "Biological & Disease Networks: are we ready for this enemy?".
30. 2011 UK Annual Condensed Matter Physics Conference, December 13-16, 2011, Manchester, England, "Statistical mechanics of complex networks: from the WWW to the cell".
31. World Economic Forum, January 25-29, 2012, Davos, Switzerland, Managing complexity (1/26) and Human network dynamics (1/27) (invited panelist for both).
32. Harvard Medical School, Department of Systems Biology, February 10, 2012, Boston, MA, "Controlling networks".
33. Harvard Business School, Berkman Center, February 16, 2012, Cambridge, MA "Network Science: from Structure to Control".

34. More is Different: A Conference on Complexity, February 21-27, 2012, Nanyang Technical University, Singapore, "Human Dynamics: from human mobility to predictability" (2/12) and "Network Science: from structure to control" (2/27).
35. 3rd Workshop on Complex Networks, CompleNet 2012, Florida, March 7, 2012, "Taming complexity: controlling networks".
36. AAI 2012 Spring Symposium Series, Stanford University, CA, March 26-28, 2012, "Network science: understanding the internal organization of complex systems".
37. TEDMED 2012, Washington, DC, April 10-12, 2012, "Do your proteins have their own social network?" (invited).
38. Princeton University, PACM Distinguished Lecture Series, Princeton, NJ, "Network science: From structure to control".
39. Network modeling - Methods and applications in biology, medicine and sociology, Oslo, Norway, May 6-8, 2012, "Network science: from structure to control".
40. Mathematical Physics of Complex Networks From Graph Theory to Biological Physics (MapCon 2012), Dresden, Germany, May 13-15, 2012, "Network science: from structure to control".
41. MIHealth Forum, Barcelona, Spain, May 23-24, 2012, "Network medicine: rethinking diseases from network perspective" (plenary).
42. Belgian Physical Society, Brussels, Belgium, May 30, 2012, "Taming complexity: from understanding to controlling networks" (plenary).
43. The International School and Conference on Complex Networks, Northwestern University, IL, June 19-22, " Do your proteins have their own social network " (keynote).
44. BIG Idea [24]7, New York, NY, June 27, 2012, "Linked: data, social networks, and human behavior".
45. Institute of Advanced Studies, Lucca, Italy, July 4, 2012, "Network science: from structure to control".
46. Medical Systems Biology: Dynamics of Disease. University of Manchester, England, August 21-23, 2012, (video conference) "Network medicine: from cellular networks to the human disease".
47. NetSci High Summer Workshop, Boston University, Boston, MA, August 21-25, 2012, (documentary discussion), "Connected: The Power of Six Degrees".
48. Annual Meeting of the New Champions 2012, World Economic Forum, Tianjin, China, September 11-13, 2012, "An Insight, an Idea with Albert-Laszlo Barabasi", (joint with Cesar Hidalgo) "The Power of Networks" and (panel) "Mastering complexity" (invited).
49. International Conference on: Towards Mathematical Foundations of Complex Network Theory, Kyoto University, Japan, September 14-16, 2012, "The architecture of complexity: From the topology of the WWW to the structure of the cell" (keynote).

50. Boston University Alumni Reunion, Department of Physics, Boston, MA, September 21-22, 2012, "Taming Complexity: Controlling Networks" (keynote).
51. World Summit on Innovation & Entrepreneurship, Boston, MA, September 26-28, 2012, "Big Data. Bigger Decisions: Hidden Tensions, Smarter Innovations" (panel).
52. Sogeti Executive Summit 2012: Recorded Future, London, UK, October 1-2, 2012, "Bridging the gap to the new paradigm – When conventional wisdom is wrong" (keynote).
53. University of Rochester, David L. Dexter Lecturer, Rochester, MA, October 10, 2012, (colloquium) "The Statistical Physics of Complex Networks: From Structure to Control".
54. University of Rochester, David L. Dexter Lecturer, Rochester, MA, October 10, 2012, (public) "Human Dynamics: Where Will You Be Tomorrow At 3pm?".
55. Course: Introduction to Network Medicine, Harvard Catalyst, Cambridge, MA, October 15, 2012, "Network Medicine".
56. Global Empowerment Meeting 2012 (GEM2012), Cambridge, MA, October 24-25, 2012, "The role of networks in building prosperity" (panel).
57. Quant Invest: Manager vs. Machine, Paris, France, November 6-7, 2012, "Unveiling and Controlling Networks: From Finance to Organizations" (keynote).
58. Systems Biology Approaches to Drug Discovery: Single Gene Targeting is Not Enough, New York Academy of Science, New York City, New York, December 11, 2012, "Network Medicine: Rethinking Diseases from a Network Perspective" (invited).
59. DLD 2013: Digital - Life - Design, Munich, Germany, January 20-22, 2013, "Bursts".
60. World Economic Forum Annual Meeting 2013, Resilient Dynamism, Davos, Switzerland, January 23-27, 2013 (invited participant).
61. ASME 2013 2nd Global Congress on NanoEngineering for Medicine and Biology (NEMB2013), Boston, MA, February 4-6, 2013, "Multiscale modeling in biology and medicine" (plenary).
62. FuturICT Workshop at MIT Media Lab, Cambridge, MA, February 13-14, 2013, "Science of Impact".
63. Colloquium, Chalmers University of Technology, Gothenburg, Sweden, March 8, 2013, "Statistical mechanics of complex networks".
64. 2013 Graph Exploitation Symposium, MIT Endicott House, Dedham, MA April 16, 2013, "Complex Networks: From the structure of the WWW to cellular organization".
65. Cambridge Network Day 2013, Cambridge, UK, May 7, 2013, "Network Science: From structure to control".
66. NetSci 2013: International School and Conference on Network Science, Copenhagen, Denmark, June 3-7, 2013, "Network Science Book (iPad)".

67. XXXIII Dynamic Days Europe, Center for Biomedical Technology, Madrid, Spain, June 6-7, 2013, "Taming complexity: Controlling networks".
68. NECSI Summer School, New England Complex Systems Institute, Cambridge, MA, June 19, 2013, "Complex Networks: From the structure of the WWW to cellular organization".

4. How have the results been disseminated to communities of interest?

Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

Note: Publications are reported in Appendix B: Products.

Write your response in here.

Our work, published in:

C. Song, Z. Qu, N. Blumm, and A.-L. Barabási, Limits of Predictability in Human Mobility, *Science* 327, 1018-1021 (2010). It has been Featured in multiple media outlets and received hundreds of citations.

Our work on “Controllability of complex networks”, *Nature* 473, 167 (2011), has been highlighted in *Nature* cover story; *Nature News&Views*; *Science News&Analysis*; *ScienceNews*; *Wired*; *ScienceDaily*; *PHYSORG.com*; *MITNews*; *MITspotlight*; *News @Northeastern*. It also Collected over 300 citations in less than two year.

Our work on “Ranking stability and super-stable nodes in complex networks”, *Nature Communications* 2, 1-7 (2011), has been highlighted in *News @Northeastern*.

5. What do you plan to do during the next reporting period to accomplish the goals?

If there are no changes to the DTRA-approved plan for this effort, state “No Change.” In cases where there are anticipated changes, describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

Write your response in here.

Project ended.

Appendix B: Products

The products from an effort demonstrate the excellence and significance of the research and the efficacy with which the results are being communicated to colleagues, potential users, and the public. Publications are the characteristic product of research. Many projects (though not all) may develop products other than publications. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report".

In the Products Section, the PI must address the following five (5) product types:

For paper, book and other publications your status choices are the following: Accepted, Awaiting Publication, Published, Submitted, Under Review and Other

1. Publications, conference papers, and presentations: Report ONLY the major publication(s) resulting from the work under this award DURING THE REPORTING PERIOD. There is no restriction on the number.

- Journal publications. List peer reviewed articles or papers appearing in scientific, technical, or professional journals. Include any peer reviewed publication in the periodically published proceedings of a scientific society, a conference, or the like. A publication in the proceedings of a one-time conference, not part of a series, should be reported under "Books, or other non-periodical, one-time publications." Identify for each publication: author(s), title, journal, volume, year, page numbers, status of publication, and acknowledgement of federal support.

Note: Please do not use abbreviations for the Journal name.

Write your responses in here.

1. K.-L. Goh, A.-L. Barabási, Burstiness and memory in complex systems, *Europhysics Letters* 81, 48002 (2008).
2. J. Candia, M. C. Gonzalez, P. Wang, T. Schoenharl, G. Madey, A.-L. Barabási, Uncovering individual and collective human dynamics from mobile phone records, *Journal of Physics A: Mathematical and Theoretical* 41, 1-11 (2008).
3. M. C. González, C. A. Hidalgo, A.-L. Barabási, Understanding individual human mobility patterns, *Nature* 453, 779-782 (2008).
4. D. Lazer, A. Pentland, L. Adamic, S. Aral, A.-L. Barabási, D. Brewer, N. Christakis, N. Contractor, J. Fowler, M. Gutmann, T. Jebara, G. King, M. Macy, D. Roy, M. Van Alstyne, *Computation Social Science, Science* 323, 721-724 (2009).
5. P. Wang, M. Gonzalez, C. A. Hidalgo, A.-L. Barabási, Understanding the spreading patterns of mobile phone viruses, *Science* 324, 1071-1076 (2009).
6. A.-L. Barabási, Scale-Free Networks: A Decade and Beyond, *Science* 325, 412-413 (2009).
7. P. Wang, M. C. Gonzalez, Understanding spatial connectivity of individuals with

- non-uniform population density, *Philosophical Transactions of The Royal Society A* 367, 3321-3329 (2009).
8. J. Bagrow, T. Koren, Investigating bimodal clustering in human mobility, 2009 Inter-national Conference on Social Computing, SCMP09, Vancouver (To Appear 2009).
 9. C. Song, Z. Qu, N. Blumm, A.-L. Barabási, Limits of Predictability in Human Mobility, *Science* 327, 1018-1021 (2010).
 10. Y.-Y. Ahn, J. P. Bagrow, S. Lehmann, Link communities reveal multiscale complexity in net-works, *Nature* 1038, 1-5 (2010).
 11. J. Bagrow, P. Wang, A.-L. Barabasi, Collective response of human populations to large-scale emergencies *PLoS One* 6:3, 1-8 (2011).
 12. C. Song, T. Koren, P. Wang, A.-L. Barabási, Modeling the scaling properties of human mobility (in press, *Nature Physics*).
 13. Liu, Y.-Y., Slotine, J.-J. & Barabási, A.-L. Controllability of Complex Networks. *Nature* 473, 167-173, (2011).
 14. Ghoshal, G. and Barabási, A.-L. Ranking stability and super-stable nodes in complex networks. *Nature Communications* 2, 1-7 (2011).
 15. Y.-Y. Liu, J.-J. Slotine, A.-L. Barabási, Few inputs can reprogram biological networks (reply by Liu et al.) *Nature* 473, 167-173 (2011).
 16. D. Wang, D. Pedreschi, C. Song, F. Giannotti, A.-L. Barabasi, Human Mobility, Social Ties, and Link Prediction, *ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD)*, (2011).
 17. F. Simini, M. González, A. Maritan, A.-L. Barabási, A universal model for mobility and migration patterns, *Nature* 484, 96-100 (2012).
 18. Y.-Y. Liu, J.-J. Slotine, A.-L. Barabasi, Control centrality and hierarchical structure in complex networks, *PLoS One* 7, e44459 (2012).
 19. M. Pósfai, Y.-Y. Liu, J.-J. Slotine, A.-L. Barabási, Effect of correlations on network controllability, *Scientific Reports* 3:1067, 1-7 (2013).
 20. Y.-Y. Liu, J.-J. Slotine, A.-L. Barabási, Observability of complex systems, *Proceedings of the National Academy of Sciences* 110, 1-6 (2013).
 21. T. Jia, Y.-Y. Liu, E. Csóka, M. Pósfai, J.-J. Slotine, A.-L. Barabási, Emergence of bimodality in controlling complex networks, *Nature Communications* 4:2002, 1-6 (2013).
 22. B. Barzel, A.-L. Barabási, Network link prediction by global silencing of indirect correlations, *Nature Biotechnology* 31: Num 8, 1-8 (2013).
 23. T. Jia, A.-L. Barabási, Control capacity and a random sampling method in exploring controllability of complex networks, *Scientific Reports* 3:2354, 1-6 (2013).
 24. B. Barzel, A.-L. Barabási, Universality in network dynamics, *Nature Physics* 9, 673-681 (2013).

- Books or other non-periodical, one-time publications. Report any book, monograph, dissertation, abstract, of the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-

time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s), title, editor, title of collection (if applicable), bibliographic information, year, type of publication (book, thesis or dissertation, other), status of publication (published, accepted, awaiting publication, submitted, under review, other), and acknowledgement of federal support.

Other publications, conference papers and presentations. Identify any other publication, conference papers, and or presentations not reported above. Specify the status of the publication as noted above.

Write your responses in here.

“A.-L. Barabasi, Bursts: The Hidden Pattern Behind Everything We Do” (Dutton, NY, April 2010)

2. Website(s) or other Internet site(s)

List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified in this section.

Website(s) or other Internet site(s):

List your websites in here.

We designed a website for the network controllability project.

<http://barabasilab.neu.edu/projects/controllability/>

A movie about network controllability was posted on Youtube:

<http://www.youtube.com/watch?v=9-q2qpOJfkg>

Online textbook on Network Science:

<http://barabasilab.neu.edu/networksciencebook/>

3. Technologies or techniques

Identify technologies or techniques that have resulted from the research activities. Describe the technologies or techniques and how they are being shared. NOTE: DTRA does not anticipate that ANY basic or fundamental research award will produce technologies.

Technologies or techniques:

Write your responses in here.

We have developed several technologies pertaining to control, observability and inference. They listed below.

4. Inventions, patent applications, and/or licenses

Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Inventions, patent applications, and/or licenses:

Write your responses in here.

Title: "Method of Statistical Association of Network Services and Cyber-Threats"
US Provisional Application No. 61/892,125 -- Inventors: S. Gil, et al; Date of Filing: October 17, 2013
Our File No. INV-14036 -- Co-Authors: A.-L. Barabasi

Title: "Method for Predicting Future Impact and Popularity:
US Provisional Application No. 61/817,712 -- Inventors: A.-L. Barabasi, et al; Date of Filing: April 30, 2013
Our File No. INV-13077 -- Co-Authors: Chaoming Song, Dashun Wang

Title: "Silencing Method for Predicting Direct Causal Links"
US Provisional Application No. 61/827,135 -- Inventors: B. Barzel, et al; Date of Filing: May 24, 2013
Our File No. INV-13096.01 -- Co-Authors: A.-L. Barabasi

Title: "Method for Identifying Sensors for Complex Systems"
U.S. Provisional Application No. 61/778,027 -- nInventors: A. Barabasi, et al; Date of Filing: March 12, 2013
Our File No. INV-13063.01 -- Co-Authors: Yang-Yu Liu and Jean-Jacques Slotine

5. Other products

Identify any other significant products that were developed under this project. Describe the product and how it is being shared.

Other products:

Write your responses in here.

We have developed a new on textbook on Network Science.

Appendix C: Participants & Other Collaborating Organizations

Providing information the project participants and collaborating organizations allows an assessment of performance in promoting partnerships and collaborations In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report".

In the Participants & Other Collaborating Organizations Section, the PI must address the following three (3) questions:

1. What individuals have worked on the project? Provide the following information for: 1) principal investigator(s)/project director(s) (PIs/PDs); and 2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).

NUMBER OF PIS/CO-PIs: 1

Numbers of individuals aligned to the following categories who worked one person month during the reporting period:

Write responses in here:

Albert-Laszlo Barabasi

POST-DOCTORAL FELLOWS: 3

Describe how the Post-Doctoral Fellows individuals contributed to the project:

Write responses in here:

Yang-Yu Liu – Analyzed all the empirical data and did all the analytical and numerical calculations. Edited the manuscript. Gourab Ghoshal – Participated in conceptualizing the project. Developed the analytical framework and performed all theoretical calculations and numerical simulations. James Bagrow – Analyzed all the empirical data and did all the analytical and numerical calculations. Edited the manuscript. Tao Jia – Participated in conceptualizing the project. Developed the analytical framework and performed all theoretical calculations and numerical simulations. Gathered data and performed numerical analysis.

If the Post-Doctoral Fellows were involved with international collaborations, describe the collaboration, identify the country, and detail any travel to that country with the duration of the stay:

Write responses in here:

Nothing to Report.

GRADUATE STUDENTS: 1

Describe how the Graduate Students individuals contributed to the project:

Write responses in here:

Marton Posfai did extensive studies on the effect of network correlations on its controllability.
Dashun Wang was involved in several projects pertaining to network robustness under emergencies.

If the Graduate Students were involved with international collaborations, describe the collaboration, identify the country, and detail any travel to that country with the duration of the stay:

UNDERGRADUATE STUDENTS: 0

Describe how the Undergraduate Students individuals contributed to the project:

If the Undergraduate Students were involved with international collaborations, describe the collaboration, identify the country, and detail any travel to that country with the duration of the stay:

RESEARCH TECHNICIANS: 1

Describe how the Research Technicians contributed to the project:

Write responses in here:

Dr. Alec Pawling (DBA), provided database assistance and advice on programming issues.

If the Research Technicians were involved with international collaborations, describe the collaboration, identify the country, and detail any travel to that country with the duration of the stay:

Write responses in here:

Nothing to Report.

2. What other organizations have been involved as partners?

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that have been involved with the project.

Other organizations:

List in here:

- Center for Cancer Systems Biology, Dana-Farber Cancer Institute, Harvard Medical School, Boston, Massachusetts 02115, USA.
- Nonlinear Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
- Department of Mechanical Engineering and Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
- Department of Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts 02115, USA.

3. Have other collaborators or contacts been involved?

Some significant collaborators or contacts within the recipient's organization may not be covered by "What people have worked on the project"? Likewise, some significant collaborators or contacts outside the recipient's organization may not be covered under "What other organizations have been involved as partners"? It is likely that many recipients will have no other collaborators or contacts to report.

Collaborators or contacts:

List in here:

Nothing to Report.

Appendix D: Impact

Information on the impact of the research demonstrates how the investment increases the scientific body of knowledge, enlarges the pool of people trained to develop that knowledge and techniques or put it to use, and improves the physical, institutional, and information resources that enable those people to get their training and perform their functions. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report".

In the Impact Section, the PI must address the following seven (7) questions:

1. What is the impact on the development of the principal discipline(s) of the project?

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research and/or pedagogical methods in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

Note: Please include the Hirsch Index for the PI in the response to this question.

Write your responses in here.

Our results indicate that many aspects of controllability can be explored exactly and analytically for arbitrary networks if we combine the tools of network science and control theory, opening new avenues to deepening our understanding of complex systems.

The PI's current Hirsch Index is 87 (calculated by Google Scholar).

The impact factors of our publications are:

1. Nature v407: 36.101
2. Nature Communication v2: 10.015
3. Proceedings of the National Academy of Sciences v110: 9.737
4. Nature Biotechnology v31: 32.44
5. Nature Physics v9: 19.352

2. What is the impact on other disciplines?

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

Impact on the development of the principal discipline(s) or other disciplines (questions 1 and 2):

Write your responses in here.

The results on network's controllability raise many interesting questions. Answers to those questions are expected to have significant impact on many other disciplines, such as control theory, graph theory, and statistical physics.

3. What is the impact on the development of human resources?

Description:

Write your responses in here.

Three postdocs participated in the project and they were trained to perform cutting edge research on network science. One of the postdocs, James Bagrow is now a research assistant professor at University of Vermont. Another, Chaoming Song, has relocated to the University of Miami and Tao Jia is at Rensselaer Polytechnic Institute as a postdoctoral research associate. Dashun Wang is at IBM and Yang-Yu Liu moved to a faculty position at Harvard University and Baruch Barzel is a postdoc, also, at Harvard University

4. What is the impact on physical, institutional, and information resources that form infrastructure?

Describe ways, if any, in which the project made an impact, or is likely to make an impact, on physical, institutional, and information resources that form infrastructure, including:

- Physical resources such as facilities, laboratories, or instruments;
- Institutional resources (such as establishment or sustenance of societies or organizations);
- Information resources, electronic means for accessing such resources or for scientific communication, or the like.

Write your responses in here.

Nothing to Report.

5. What is the impact on technology transfer?

Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:

- Transfer of results to entities in government or industry;
- Adoption of new practices

Write your responses in here.

We are in the process to transfer the patent applications to industry.

6. What is the impact on society beyond science and technology?

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:

- Improving public knowledge, attitudes, skills, and abilities;
- Changing behavior, practices, decision making, policies (including regulatory policies), or social actions;
- Improving social, economic, civic, or environmental conditions.

Write your responses in here.

Our work on “Controllability of complex networks”, *Nature* 473, 167 (2011), has been highlighted in *Nature* cover story; *Nature* News&Views; *Science* News&Analysis; ScienceNews; Wired; ScienceDaily; PHYSORG.com; MITNews; MITspotlight; News@Northeastern.

Our work on “Ranking stability and super-stable nodes in complex networks”, *Nature Communications* 2, 1-7 (2011), has been highlighted in News@Northeastern.

Other Impact (questions 4, 5 and 6):

Write your responses in here.

Nothing to Report.

7. What dollar amount of the award’s budget is being spent in foreign country(ies)?

Describe what percentage of the award’s budget is being spent in foreign country(ies). If more than one foreign country, identify the distribution between the foreign countries.

Percent: Country: Nothing to Report

Appendix E: Changes/Problems

The PI is reminded that the award may contain specific instructions regarding significant changes in a project or its direction. See the Terms and Conditions of the award document for instructions regarding the submission of these requests.

In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report".

In the Changes/Problems Section, the PI must address the following five (5) issues:

1. Changes in approach and reasons for change.

Describe any changes in approach during the reporting period and reasons for these changes.

2. Actual or anticipated problems or delays and actions or plans to resolve them.

Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

3. Changes that have a significant impact on expenditures.

Describe changes during the reporting period that may have a significant impact on expenditures, e.g. delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

4. Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards.

Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, and/or biohazards during the reporting period. If required, were these changes approved by the applicable institution committee and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

5. Change of primary performance site location from that originally proposed.

Identify any change to the primary performance site location identified in the proposal, as originally submitted.

Changes/Problems:

Write your responses in here.

Nothing to report.