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14. ABSTRACT The main goal of this project is to establish a fundamental analytical and design framework for highly resilient wireless and sensor networks based on the study of the qualitative and quantitative properties of the largest connected component. Building on our recent promising results in the field of percolation, we propose to design network structures and algorithms to greatly enhance the resilience of high-performance wireless and sensor networks within challenging and dynamic environments. This proposed effort involves further enhancing our understanding of percolation processes and phase transition in networks with general spatial node distributions, multiple transmission power levels, and channel fading. It also					
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Report Title

Final Report for "Analysis and Design of Highly Resilient Wireless and Sensor Networks"

ABSTRACT

The main goal of this project is to establish a fundamental analytical and design framework for highly resilient wireless and sensor networks based on the study of the qualitative and quantitative properties of the largest connected component. Building on our recent promising results in the field of percolation, we propose to design network structures and algorithms to greatly enhance the resilience of high-performance wireless and sensor networks within challenging and dynamic environments. This proposed effort involves further enhancing our understanding of percolation processes and phase transition in networks with general spatial node distributions, multiple transmission power levels, and channel fading. It also involves analysis of network resilience to correlated and cascading node failures, investigating resilience in mobile networks, and developing distributed control algorithms to achieve network resilience using limited communication overhead.

Major accomplishments over the period covered by the grant fall into three general areas: 1) improvement of the analytical characterization of the critical threshold for general random geometric graphs with heterogeneous transmission power levels and channel fading, 2) new analysis of the resilience to correlated and cascading node failures in wireless networks, and 3) new analysis of percolation processes in mobile wireless networks, and characterization of the latency for information dissemination in mobile wireless networks.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Jian Cao and Edmund M. Yeh, "Asymptotically Optimal Multiple-access Communication via Distributed Rate Splitting." IEEE Transactions on Information Theory, Vol. 53, No. 1, January 2007, pp. 304-319.

Number of Papers published in peer-reviewed journals: 1.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. Yufang Xi and Edmund M. Yeh, "Distributed Optimization Algorithms for Network Coding." INFORMS Annual Meeting, Pittsburgh, PA, November 6, 2006.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. Zhenning Kong and Edmund M. Yeh, "On the Critical Density for Percolation in Random Geometric Graphs." Proceedings of the Information Theory and Applications Workshop, San Diego, CA, January 29 - February 2, 2007.

2. Yufang Xi and Edmund M. Yeh, "Distributed Algorithms for Maximum Throughput in Wireless Networks." Proceedings of the Fourteenth European Signal Processing Conference. Florence Italy, September 4 - 8, 2006.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 2

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. Zhenning Kong and Edmund M. Yeh, "Characterization of the Critical Density for Percolation in Random Geometric Graphs." Proceedings of the 2007 International Symposium on Information Theory, Nice, France, June 24 - 29, 2007.
2. Edmund M. Yeh and Randall A. Berry, "Throughput Optimal Control of Wireless Networks with Two-hop Cooperative Relaying." Proceedings of the 2007 International Symposium on Information Theory, Nice, France, June 24 - 29, 2007.
3. Yufang Xi and Edmund M. Yeh, "Spectrum Allocation in Wireless Networks with Duplexing Constraints." Proceedings of the 2007 International Symposium on Information Theory, Nice, France, June 24 - 29, 2007.
4. Zhenning Kong and Edmund M. Yeh, "Analytical Lower Bounds on the Critical Density in Continuum Percolation." Proceedings of the Workshop on Spatial Stochastic Models in Wireless Networks (SpaSWiN), Limassol, Cyprus, April 16, 2007.
5. Jian Ni, Sekhar Tatikonda and Edmund M. Yeh, "A Large-Scale Distributed Traffic Matrix Estimation Algorithm." Proceedings of the Global Telecommunications Conference, San Francisco, CA, November 27-December 1, 2006.
6. Ming Cao, Daniel A. Spielman and Edmund M. Yeh, "Accelerated Gossip Algorithms for Distributed Computation." Proceedings of the Allerton Conference on Communication, Control, and Computing. Monticello, IL, September 27 - 29, 2006

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 6

(d) Manuscripts

1. Yufang Xi and Edmund M. Yeh, "Distributed Algorithms for Spectrum Allocation, Power Control, Routing, and Congestion Control in Wireless Networks." Submitted to IEEE Transactions on Networking, April 2007.
2. Yufang Xi and Edmund M. Yeh, "Throughput Optimal Distributed Control of Stochastic Wireless Networks." Submitted to IEEE Transactions on Networking, September 2006.

Number of Manuscripts: 2.00

Number of Inventions:

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Zhenning Kong	0.92
FTE Equivalent:	0.92
Total Number:	1

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

- The number of undergraduates funded by this agreement who graduated during this period: 0.00
- The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00
- The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00
- Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00
- Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00
- The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00
- The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Final Report

1 Statement of Problems Studied

The major problems investigated as a part of this project include:

1. Improve the analytical characterization of the critical threshold for general geometric graphs. Apply the results to analyze resilience of wireless and sensor networks with multiple transmission power levels and channel fading.
2. Develop analysis, designs, and algorithms to improve resilience to correlated and cascading node failures in wireless and sensor networks.
3. Develop analysis of percolation processes and designs for higher resilience to random node failures in mobile wireless and sensor networks.

2 Summary of Most Important Results

Over the one-year period covered by this grant, the PI has made significant progress in solving the major research problems outlined above.

Connectivity and Resilience of General Random Geometric Graphs. Building on the PI's previous results on the characterization of the critical density for percolation in random geometric graphs with constant transmission radii, we examined more general random geometric graphs where the nodes have heterogeneous transmission power capabilities, and the links experience channel fading.

To model random geometric graphs with heterogeneous transmission powers, the PI considered random geometric graphs where the transmission radii are not fixed, but are independently and identically distributed according to a given distribution. Under this assumption, it was found that the analytical technique based on the clustering effect developed by the PI for graphs with constant radii can be applied to the case of heterogeneous radii as well. The clustering effect was used to produce a lower bound to the critical density for percolation. The PI also used a mapping from continuum percolation to discrete percolation on a triangular lattice to produce an upper bound on the critical density. These bounds are the first known analytical bounds for random geometric graphs with heterogeneous transmission radii.

Due to noise, fading and multi-user interference, communication links in wireless networks are unreliable. Even when two nodes lie within each others transmission range, a viable communication link may not exist between the two nodes due to path-loss and fading. To capture this effect, the PI studied percolation processes in wireless networks with static unreliable links, where each link of the network is functional (i.e., active) with some probability (which may depend on the distance between the two nodes) independently of all other network links. This is a specific case of the so-called random connection model. The PI employed the cluster coefficient method and coupling methods to obtain lower and upper bounds on the critical density for this model. In wireless environments with time-varying channels, each link may dynamically switch between the active and inactive states. To investigate the effect of this dynamic behavior on percolation-based connectivity, the PI further studied percolation processes in wireless networks with dynamic unreliable links. The PI showed that a phase transition exists in these dynamic networks under certain conditions, and the critical density for this model is the same as the one for static networks with the same parameters.

Correlated and Cascading Node Failures. The PI has studied the problem of wireless network resilience to node failures from a percolation-based perspective. In practical wireless networks, it is often the case that nodes with larger degrees (i.e., more neighbors) are more likely to fail. The PI has modeled this phenomenon as a degree-dependent site percolation process on random geometric graphs. In particular, the PI obtained analytical conditions for the existence of phase transitions within this model. Furthermore, in networks carrying traffic load, the failure of one node can result in redistribution of the load onto other nearby nodes. If these nodes fail due to excessive load, then this process can result in cascading failure. The PI has analyzed this cascading failures problem in large-scale wireless networks, and has shown that it is equivalent to a degree-dependent site percolation on random geometric graphs. The PI obtained analytical conditions for cascades in this model. The above conditions for percolation and non-percolation as a measure of network resilience to correlated and cascading node failures are the first known results of this kind in the field.

Percolation and Resilience in Mobile Wireless Networks. In many military wireless and sensor networks consisting of soldiers, ships, airplanes, unmanned aerial and underwater vehicles, nodes are highly mobile. In this moving environment, connectivity in the network should not be assessed at a fixed time instant. Rather, two nodes can exchange information, and thus share a link, if they can decode each other's signals at some point in time. Since different pairs of nodes can share links at different points in time, connectivity must also be analyzed over time. This led the PI to study percolation over time in mobile wireless networks.

In wireless networks, node mobility may be exploited to assist in information dissemination over time. The PI has analyzed the latency for information dissemination in large-scale mobile wireless networks. By using a new analytical technique which maps a random network of mobile nodes to a random network of stationary nodes with dynamic links, the PI has shown that under the constrained i.i.d. mobility model (where at each discrete time

instant, each node can move to a point in a constrained region, chosen uniformly at random over the region), when the network density satisfies a certain condition, almost all nodes in the networks can receive the source message eventually with high probability. Moreover, the PI has shown that, ignoring propagation delay, the latency for information dissemination scales *linearly* with the initial Euclidean distance between the sender and the receiver if the network is in the subcritical (non-percolated) phase, and the latency scales *sub-linearly* with the distance if the network is in the supercritical (percolated) phase.