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13. ABSTRACT (Maximum 200 Words) Based on analogues from physical systems and science, we have investigated, developed, and evaluated prediction and control strategies for assured operation in high data rate, mobile wireless networks. The dynamic wireless networks, and their optimization, were analyzed by methods used in molecular dynamics. A significant outcome of this research is an application for a patent as follows: “Systems, Methods, Devices, and Computer Program Products for Control and Performance Prediction in Wireless Networks.” We considered wired as well as wireless networks, and we addressed the fundamental problems of how information should be fused over a network. In addition, we studied the performance and tradeoffs of integration of cooperative communication with network coding for assurance of information transfer.					
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Final Report
**Quantifying and Assuring Information Transfer in Dynamic Heterogeneous
Wireless Networks**

1. Principal Investigator Name: Stuart Milner
Co-Principal Investigators: Christopher C. Davis, Zygmunt J. Haas, P. R. Kumar
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Dr. Robert Bonneau
7. **Accomplishments:**

University of Maryland (Stuart Milner, Christopher C. Davis)

We investigated backbone-based wireless networks, which use a two-tiered architecture, where a set of flat ad-hoc wireless networks with limited communication capabilities are interconnected through a broadband wireless mesh backbone network. The latter comprises higher capability nodes that use directional wireless communications (FSO and/or directional RF) to aggregate and transport traffic from end users or hosts. Our research has uniquely focused on prediction and control of such mobile wireless backbones in order to provide assured end-to-end connectivity and coverage to mobile end users.

Assuring the robustness of such dynamic, wireless networks requires self-organization mechanisms to assure end-to-end broadband connectivity. We have developed a framework to provide prediction and control strategies for assured network operation that are interoperable with the Internet protocol suite. To investigate these prediction and control strategies, we draw an analogy between a set of interconnected communication nodes and a molecule in which the bonds between atoms are representative of the links in the equivalent network. The dynamics of the network, and its optimization, can be analyzed by the methods of molecular dynamics. Links are modeled as bonds described by potential energy functions, such as the Morse potential, and a global description of the stability of the network can be obtained by a normal mode analysis (NMA). Effective forces act on nodes, which include the effects of power

control, link length, and channel characteristics. A molecular re-arrangement or fragmentation occurs because this reduces the potential energy. In the same way a network can undergo topological reconfiguration, and an adaptive control strategy can be used to release, retain or reconfigure communication links for network performance optimization.

In addition, we developed new models and algorithms for control and optimization of these networks under real world physical constraints. First, we proposed a mathematical modeling method for the self-organization and optimization of the networks by taking into account physical constraints in terms of minimum distance threshold, power limitations, and capacity of backbone nodes. Second, using only local information, we developed new flocking rules and a corresponding algorithm to autonomously assure, control and optimize network performance in a practical way. Associated physical constraints checking algorithms are also developed. Third, we use particle swarm optimization (PSO), a stochastic global optimization algorithm, to optimize an hierarchical heterogeneous wireless networks (HHWN) directly with a hybrid evaluation function and using global information.

We developed a software tool in MATLAB that allows the modeling and simulation of dynamic heterogeneous wireless networks with different design parameters. Terminal nodes move according to mobility models and our control methods are used to make backbone nodes adjust their locations until convergence to the optimal backbone configuration. In addition, we integrated the MATLAB models with OPNET, a modeling and simulation package, in order to provide the generalization of our prediction and control models to internet protocols and operation.

We introduced the Morse potential as an alternative link energy function that leads to a hybrid topology control methodology where communication links are retained, released or reconfigured based on their communications role within the network architecture.

A convex energy function with exponential constraint was used to model the link retention process, where attraction forces drastically increase their magnitude when reaching physical constraints. The Morse potential, on the other hand, which models the energy saturation leading to bond breaks in molecular systems, is used to model the link release process, in which attraction forces reduce their magnitude when reaching physical constraints.

In our simulations, backbone-to-backbone links, of critical importance in the network architecture, were modeled using the convex model with exponential constraint, while the backbone-to-terminal links are modeled using the Morse potential. We measured the average number of SD connections maintained and showed a significant improvement when using the hybrid energy model. The use of the Morse potential at the backbone-to-terminal links allows the network to release high cost links that have an effect on the overall assurance of end-to-end connectivity. Results suggest a more significant improvement the more restrictive the physical constraints, such as the maximum transmission power and the mobility of terminal nodes.

Of key importance is the analysis of the convergence and robustness of molecular-based optimization methods, including the characterization of the multiple equilibrium configurations that might arise from the adoption of non-convex potentials.

Experimental results confirm that our flocking algorithm (FA) and PSO both perform well for the optimization of an HHWN in terms of performance metrics such as energy

cost, loss of connections, and number of SD connections. PSO produces superior performance but results in a relatively slow convergence speed and only favors the dynamics of backbone nodes in the x-y plane. FA is capable of delivering fast convergence speed while achieving satisfactory solutions for an HHWN. Furthermore, with the use of FA, the backbone nodes can move flexibly in 3D space by taking into account the repulsion force from the physical constraints (e.g. mountains).

We employed molecular-based systems to investigate the prediction of link degradation leading to a self-diagnosing ability within the network in the subsequent evolutions of its (re)configuration or topology. By modeling the network as a set of convex (connected) and non-convex (non-connected) springs the network entity can be thought of as a giant molecule. The analysis of the network evolution will follow molecular dynamics and the contribution of each backbone node's movement can be defined as a consequence (positive or negative) on the overall health of the network and its available connectivity. We showed that this is a promising approach to predict the overall network health (cost). Our strategy involves the use of electronic structure theories (isomers) such that the network entity is modeled as a giant molecule and the communication links are thought of as chemical bonds.

Additionally, we found that understanding the flexibility of a node within a connected structure can yield results different from approaches where the algorithms are traditionally performed recursively on static network events such as link state updates. The potential energy surface (PES) methodology allows for a single calculation with the identification of a transition point between two static solutions. These analytical approaches may lead to the ability to predict when an HHWN is at a point of failure or degradation and allow topology reconfiguration to be implemented before failure occurs.

Results showed promise for identifying predicted (buffer) time prior to a reconfiguration. We found that the average buffer or prediction time prior to a topology reconfiguration is on the order of minutes, and this buffer time is related to the aggregate topology cost reduction threshold value.

Finally, we have submitted an application for a patent as follows: **Systems, Methods, Devices, And Computer Program Products for Control and Performance Prediction in Wireless Networks.** S. Milner, C.C. Davis, J. Llorca, Submitted to U.S. Patent and Trademark Office, April 10, 2012.

University of Illinois (P. R. Kumar)

Sensor networks are deployed to obtain information about the environment. The fundamental problem is that of function computation over a network. The fusion node in such networks is not interested in obtaining all the data from all the nodes. In fact that could overload the data bandwidth of the wireless or wired network. Instead the fusion node is only interested in obtaining a function of all the data. For that purpose, individual nodes can process the information that they receive, perform computations on them, and then send out appropriate information to other nodes. If viewed from an information theoretic perspective, it has the complexities of distributed source coding, the complexities of multihop wireless or wired networks, and the complexities of rate distortion. We address the fundamental problems of how nodes can perform function computation over a network, based on packets they exchange with each other. There may

be an *a-priori* distribution of data, which leads to a Bayesian perspective, or there may be a distribution free worst-case setting. One can consider block computation or one-shot computation, which incur no excessive delay of accumulating measurements. We consider symmetric Boolean function, including threshold functions, delta functions and interval functions. We consider wired as well as wireless networks. We have addressed the fundamental problems of how information should be fused over a network.

Networked control systems give rise to several new problems, which need to be resolved for successful development of such control systems. One of the most important is to develop a software framework with appropriate architecture and mechanisms for rapid, reliable, and evolvable distributed control applications. In particular, timeliness in the interaction among entities that constitute the overall control loop is one of the crucial requirements that must be provided by the platform. We have addressed the issues related to the design and implementation of such mechanisms to support timeliness requirements. We have designed real-time enhancements to Etherware, a middleware for distributed control systems that has been developed in the Information Technology Convergence Laboratory at the University of Illinois. We have further evaluated the performance of the designed middleware through a distributed inverted pendulum control application. We have demonstrated the satisfactory performance of the unstable system even under several sophisticated run-time functionalities such as component upgrade and migration. We have demonstrated that stability is maintained even under each of these tests as well as a computational stress test.

Cornell University (Zygmunt Haas)

We have:

Continued and concluded the study of performance and tradeoffs of integration of Cooperative Communication with Network Coding for assurance of information transfer.

Proposed and studied the use of Network Coding for secure communication in wireless ad hoc and sensor networks.

Proposed and studied novel broadcasting schemes in highly dynamic networks, so as to significantly improve network availability.

Initiated a new study on Collaborative Reporting and Transmission in sensor networks for exploiting the inherent redundancy of WSN nodes' readings so as to increase the efficiency of radio transmissions.

Concluded the study of the use of Network Coding in Delay Tolerant Networks for improving the tradeoff among the three parameters: delivery assurance, delivery delay, and energy consumption.

8. Archival Publications (published) during contract period:

University of Maryland

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3. Hemant Kowshik and P. R. Kumar, **Optimal Function Computation in Directed and Undirected Graphs**. To appear in IEEE Transactions on Information Theory.
4. I-Hong Hou and P. R. Kumar, **Queueing Systems with Hard Delay Constraints: A Framework and Solutions for Real-Time Communication over Unreliable Wireless Channels**. To appear in Queueing Systems: Theory and Applications.
5. Kyoung-Dae Kim and P. R. Kumar, **A Real-Time Middleware for Networked Control Systems and Application to an Unstable System**. Submitted to IEEE Transactions on Control Systems Technology. Submitted June 3, 2011.
6. Yan Gao, Chee Wei Tan, Ying Huang, Zheng Zeng and P. R. Kumar, **Characterization of Mean Delays and Optimization of Delay Guarantees for Non-homogeneous Flows in IEEE 802.11 WLANs**. Submitted to IEEE Transactions on Networking. Submitted September 20, 2011.
7. I-Hong Hou and P. R. Kumar, Real-Time **Communication over Unreliable Wireless Links: A Theory and Its Applications**. To appear in IEEE Wireless Communications Magazine. Submitted November 9, 2011.
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9. Hemant Kowshik and P. R. Kumar, **Optimal Computation of Symmetric Boolean Functions in Collocated Networks**. Submitted to IEEE Journal on Selected Areas in Communications: In-Network Computation: Exploring the Fundamental Limits. Submitted February 22, 2012.
10. Anand Muralidhar and P. R. Kumar, **Near-optimal quantization and linear network coding for relay networks**, Submitted to IEEE Transactions on Information Theory. Submitted March 11, 2012.
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Cornell University

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2. Z.J. Haas and M. Nikolov, **Towards Optimal Broadcasting, under journal consideration**, 2011
3. Y. Lee, G.Y. Lee, and Z.J. Haas, **Network-Coding-based Security for Ad Hoc Networks**, under journal consideration, 2011
4. C. Garcia-Costa, E. Egea-Lopez, J. Tomas-Gabarron, J. Garcia-Haro, Z.J. Haas, **A stochastic model for chain collisions of vehicles equipped with vehicular communications**, accepted for publications in the IEEE Transactions on Intelligent Transportation Systems, 2011
5. G.Y. Lee and Z.J. Haas, **Simple, Practical, and Effective Opportunistic Routing for Short-haul Multi-hop Wireless Networks**, IEEE Transactions on Wireless

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 9. ChuanYun Zou, Zygmunt J. Haas, and Sheng Zou, **Throughput maximization in UWB-based ad hoc networks**, SCIENCE CHINA, Information Sciences, vol.53, no.12: 2538-2547, DOI: 10.1007/s11432-010-4120-8
 10. Zygmunt J. Haas, Seung-Keun Yoon, and J.H. Kim, **Energy-Efficient Routing in Delay-Tolerant Networks**, in Green IT: Technologies and Applications, chapter 5, Springer-Verlag, 2011

9. Articles in Conference Proceedings

University of Maryland

1. David M. Coleman, Stuart D. Milner, and Christopher C. Davis, **Predicting topology (re)-configurations in mobile directional wireless networks using potential energy surfaces**, paper to be presented at the SPIE Laser Communication and Propagation through the Atmosphere and Oceans Conference, San Diego, August 12-16, 2012.
2. David Coleman, Kira Armacost, Christopher C. Davis, and Stuart D. Milner. **A Molecular-Inspired Approach for Predicting Topology Change in Directional Mobile Wireless Networks**, Proceedings of the International Conference on Intelligent Sensors, Sensor Networks and Information Processing. 6-9 December, 2011, Adelaide, Australia.
3. John Rzasa, Stuart D. Milner, Christopher C. Davis. **Design and Implementation of Pan-Tilt FSO Transceiver Gimbals for Real-Time Compensation of Platform Disturbances using a Secondary Control Network**, Proceedings the SPIE Conference on Free-Space and Atmospheric Laser Communications, San Diego California, August 24-25, 2011.
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5. Haijun Zhang, Jaime Llorca, Christopher C. Davis, and Stuart D. Milner, **A Novel Flocking Inspired Algorithm for Self-Organization and Control in Heterogeneous Wireless Networks**, Proceedings of the Sixth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), S. Marusic, M. Palaniswami, J. Gubbi, P. Corke, Eds. Brisbane Australia, 7-10 December 2010.

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3. Yan Gao, Zheng Zeng and P. R. Kumar, **Joint Random Access and Power Selection for Maximal Throughput in Wireless Networks**. Proceedings of Infocom Miniconference 2010, March 15-19, 2010, San Diego, CA.
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7. M. Anand and P. R. Kumar, **A digital interface for Gaussian relay networks: lifting codes from the discrete superposition model to Gaussian relay networks**. Proceedings of the 2010 IEEE Information Theory Workshop, pp. 465{469, January 6{8, 2010, Cairo.
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10. Hemant Kowshik and P. R. Kumar, **Optimal ordering of transmissions for Boolean function computation**. Proceedings of the 2010 IEEE International Symposium on Information Theory (ISIT 2010), pp. 1863{1867, Austin, Texas, June 13{18, 2010.
11. Roberto Solis Robles, Jason J. Haas, Jerry T. Chiang, Yih-Chun Hu, and P. R. Kumar, **Secure Network-Wide Clock Synchronization in Wireless Sensor Networks**. To appear in Proceedings of 49th IEEE Conference on Decision and Control. Atlanta, December 15{17, 2010. (Invited Paper).
12. M. Anand and P. R. Kumar, **Estimating the state of a Markov chain over a noisy communication channel: A bound and an encoder**. To appear in Proceedings of 49th IEEE Conference on Decision and Control. Atlanta, December 15{17, 2010. (Invited Paper).
13. Kyoung-Dae Kim, Sayan Mitra and P. R. Kumar, **Bounded-Reachability of Linear Hybrid Automata with a Deterministic and Transversal Discrete Transition Condition**. To appear in Proceedings of 49th IEEE Conference on Decision and Control. Atlanta, December 15{17, 2010. (Invited Paper).
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15. Yan Gao, Chee Wei Tan, Ying Huang, Zheng Zeng and P. R. Kumar, **Feasibility and Optimization of Delay Guarantees for Non-homogeneous Flows** in IEEE 802.11 WLANs, pp. 2660{2668, Proceedings of the 30th IEEE International Conference on Computer Communications (IEEE INFOCOM 2011), Shanghai, April 10{15, 2011. (Acceptance rate: 15.96%)
16. Zheng Zeng, Yan Gao, P. R. Kumar and Kun Tan, **CHAIN: Introducing Minimum Controlled Coordination into Random Access MAC**, pp. 2669{2677, Proceedings of the 30th IEEE International Conference on Computer Communications (IEEE INFOCOM 2011), Shanghai, April 10{15, 2011. (Acceptance rate: 15.96%).
17. Kyoung-Dae Kim, Sayan Mitra and P. R. Kumar, **Computing Bounded-Reach Set with Finite Precision Computations for a Class of Linear Hybrid Automata**. pp. 113-122, Proceedings of the 14th International Conference on Hybrid Systems: Computation and Control (HSCC 2011), Chicago, April 12-14, 2011.
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19. Zheng Zeng, Yan Gao, and P. R. Kumar, SOFA: **A Sleep-Optimal Fair-Attention scheduler for the Power-Saving Mode of WLANs**. pp. 87{98, Proceedings of the International Conference On Distributed Computing Systems (ICDCS 2011), June 21{24, 2011, Minneapolis. (Acceptance rate: 15%)
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pp. 5047{5051. Orlando, December 12{15, 2011. (Invited Paper).

21. I-Hong Hou and P. R. Kumar, **A Survey of Recent Results on Real-Time Wireless Networking. Proceedings of Real-time Wireless for Industrial Applications**, CPS Week, Chicago, April 11, 2011. (Invited Paper).
22. I-Hong Hou and P. R. Kumar, **Scheduling Periodic Real-Time Tasks with Heterogeneous Reward Requirements**. Proceedings of RTSS 2011: The 32nd IEEE Real-Time Systems Symposium, pp. 282-291. November 29 - December 2, 2011, Vienna, Austria.

Cornell University

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2. G. Arrobo, R. D. Gitlin, and Z.J. Haas, **Effect of Link-Level Feedback and Retransmissions on the Performance of Cooperative Networking**, *IEEE WCNC*, Quintana-Roo, Mexico, March 28-31, 2011, pp. 1131 - 1136

10. Students and Post Docs

University of Maryland

Haijun Zhang (Visiting Scholar)

David Coleman (Ph.D. candidate)

Jaime Llorca (graduated with Ph.D., Post doc at Maryland; joined Alcatel Lucent.)

Mohmamed Eslami (graduated with Ph.D., joined FDA)

Naik Agrawal (graduated with Ph.D., joined Northrop-Grumman)

University of Illinois

Kowshik, Hemant J (Graduated with PhD)

Kim, Kyoung-Dae (Graduated with PhD)

Truong, Anh (Graduated with MS)

Cornell University

Milen Nikolov (Ph.D. Candidate)

Dr. Goo Yeon Lee (Visiting Scholar)

Lin Yang (Ph.D. Candidate)

Meng-Ling Liu (Ph.D. Candidate)

Dr. Yong Lee (Visiting Scholar)

Dr. Juan Garcia-Haro (Visiting Scholar)

11. Changes in research objectives (if any):

N/A

12. Change in AFOSR program manager, if any:

N/A

13. Extensions granted or milestones slipped, if any:

N/A