Guest Editorial
Series on Molecular, Biological, and Multiscale Communication (First Issue)

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AT the leading edges of the field of telecommunications, researchers are always seeking new ways of applying the powerful analytic tools of information and communication theory. Over the past decade, attention has focused on molecular, biological, and nano-scale (or multi-scale) communications problems. These problems are described (very briefly and incompletely) as follows:

- *Molecular communication* refers to the encoding and transmission of information as patterns of molecules, which (for example) may propagate from transmitter to receiver via Brownian motion. This communication technique is inspired by chemical communication in nature across many length scales: from pheromonal communication at the macroscale, to intercellular signal transduction at the nanoscale.
- *Biological communication* refers to the communication processes among biological organisms. In one sense, this may include molecular communication, which is *biologically inspired*. However, more broadly, we also consider the application of information and communication theory to understand biological communication. Such work, which traces its origins to the very beginning of information theory, has attracted recent attention as a result of the increased interest in computational biology.
- *Multi-scale communication* refers to communication at different length scales, and particularly across multiple scales (for example, nano-to-micro). Very small systems tend to be multi-scale: for instance, a system of micrometer-scale robots may have nanometer-scale components, and need to communicate across millimeters or centimeters. Small devices have different communication capabilities from macroscale systems; for example, electromagnetic wireless communication requires a far different approach as compared to conventional systems. Molecular communication is one solution to the multi-scale problem, but many others exist (for example, carbon-nanotube networks).

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Our series, of which this is the first issue, is devoted to the above three problems, and much more: our vision is to seek new frontiers for *communications beyond conventional electromagnetism*. In this issue, we are pleased to present ten papers, which represent the high quality of work that is presently occurring in this field, and divided among our three areas of molecular, biological, and multi-scale communication.

Seven papers may be viewed as dealing primarily with molecular communication; these papers span the breadth of this rapidly growing discipline. In terms of information theory, the paper "Capacity of the Memoryless Additive Inverse Gaussian Noise Channel" presents an information-theoretic analysis of a diffusion model, where the first hitting time is modeled using the inverse Gaussian distribution. In terms of communication theory, the paper "A Unifying Model for External Noise Sources and ISI in Diffusive Molecular Communication" gives a unified communication-theoretic model of interference, both inter-symbol and inter-user; while the paper "Miniature Devices in the Wild: Modeling Molecular Communication in Complex Extracellular Spaces" considers molecular propagation and channel modeling for environments such as would be found inside the human body. Networking aspects of molecular communication are considered in the paper "TCP-like molecular communications", where a flow-control protocol is designed, bearing in mind the limitations and slow propagation speeds of molecular communication. Molecular "hardware" designs are also presented: the paper "Receivers for Diffusion Based Molecular Communication: Exploiting Memory and Sampling Rate" gives a model for a receiver design, considering the memory and sampling rate; while the paper "A Phase Locked Loop for Molecular Communications and Computations" proposes a molecular analog to the phase-locked loop. Experimental and practical approaches are also presented: the paper "Channel and Noise Models for Nonlinear Molecular Communication Systems" discusses a noise model for a "table-top" implementation of macroscale molecular communication.

Although many of the papers in the molecular communication area have biological aspects, one of our papers may be viewed as primarily biological. The paper "A Stochastic Model for Electron Transfer in Bacterial Cables" considers communication among bacteria that involves the exchange of electrons, rather than the exchange of molecules, which is possible along inter-organism filaments that are produced by some bacterial colonies.

Finally, two papers are primarily multi-scale. The paper "Externally Controllable Molecular Communication," while dealing partly with molecular communication, presents a method for controlling a small-scale system using a macroscale interface, where both the small-scale and small-to-macroscale communication is molecular. The paper "Optimizing Energy Consumption at Nanoscale" considers the important problem of optimal energy consumption in a "nanoscale" network (where nodes may span micrometers to nanometers).

We were very pleased by the response to this special issue, and we are looking forward to returning with subsequent issues: our second special issue is already in the review process, and we anticipate a third special issue to be announced by the time this article is published. As a result of the interest we have seen in our series, and the high-quality work we are able to present in this issue, we see a bright future ahead for the field of molecular, biological, and multi-scale communication.

Andrew W. Eckford (S'99–M'03) received the B.Eng. degree from The Royal Military College of Canada, Kingston, ON, Canada, in 1996 and the M.A.Sc. and Ph.D. degrees from the University of Toronto, Toronto, ON, in 1999 and 2004, respectively, all in electrical engineering. He is currently an Associate Professor with the Department of Electrical Engineering and Computer Science, York University, Toronto. He held postdoctoral fellowships at the University of Notre Dame and the University of Toronto, prior to taking up a faculty position at York University in 2006. He has also served as a Cofounder and CEO of Engage Biomechanics Inc., a spin-out company from York University. He has coauthored the textbook *Molecular Communication* (Cambridge Univ. Press, 2013). His research interests include the application of information theory to nonconventional channels and systems, particularly the use of molecular and biological means to communicate. His research has been covered in media, including Technology Review and ACM TechNews.

Dr. Eckford serves as the Chair of the IEEE ComSoc Emerging Technologies Subcommittee on Nanocommunications and is the Vice-Chair of the IEEE 1906.1 Standards Working Group, the first IEEE standard on nanoscale networking. He was also the General Chair of the 2013 13th Canadian Workshop on Information Theory. He served as a Track Editor on the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS 2013 special issue on emerging technologies.

Dilip Krishnaswamy (S'93–M'97–SM'12) received the B.Tech. (EC) from IIT Madras and the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, Champaign, IL, USA, in 1997. He was a Platform Architect at Intel, where he worked on various projects, including the Pentium4 processor development, system-on-chip (SoC) mobile platform architectures (Lead Architect for Intel's first cellular SoC—PXA800F), and cross-layer wireless multimedia optimizations in the digital home. He taught courses related to parallel computer architecture and advanced digital systems design, at the University of California, Davis, CA, USA, where he now serves on the Industrial Board of Advisors. Since late 2006, he was a Senior Staff Researcher at Qualcomm Research Center, San Diego, CA, where he worked on self-aware platforms, m2m service layer middleware, collaborative wireless nanobots for cancer therapy, Continua healthcare/oneM2M/DTN standards development, wireless distributed computing, parallel wireless communications and concurrent bandwidth aggregation, heterogeneous cooperative techniques, user modeling for distributed analytics, data-mining, and adhoc heterogeneous tunneled access technologies. He is currently a Senior Research Scientist at IBM Research, Bangalore, India. His current research interests include distributed data center systems, network functions virtualization, cognitive systems, smarter planet systems, nanoscale information processing, edge processing systems, hierarchical distributed analytics, wireless distributed computing, parallel processing, and nano-biological networks. He chaired the IEEE ComSoc Emerging Technical Subcommittee on Applications of Nanotechnologies in Communications from 2009 to 2013. He served as the Associate Editor-in-Chief of the *IEEE Wireless Communications Magazine* from 2009 to 2014. He is an Editor of the *Journal of Nano Communication Networks*. He received the Best Paper Award for research related to his thesis in the parallel processing area for the 1997 IEEE VLSI Test Symposium.

Janet L. Paluh received the Ph.D. degree in cancer biology from Stanford University, Stanford, CA, USA. She completed her postdoctoral training at the University of California, Berkeley, CA, on molecular motors and mitotic signaling. Since 2010, she has been an Associate Professor with the Nanobioscience Constellation, Colleges of Nanoscale Science and Engineering, State University of New York Polytechnic Institute, Albany, NY, USA. From 2006 to 2010, she was a Research Assistant Professor with the Department of Biology, Rensselaer Polytechnic Institute, where she then served as an Adjunct Professor from 2011 to 2012. She is internationally recognized for her innovative research on the cell cycle and cytoskeleton and for discoveries integrating nanotechnology, bioengineering, and medicine. Her current research lies at the interface between biology and nanotechnology with projects spanning stem cell biology and tissue engineering along with next-generation hybrid biosynthetic nanomachines capable of self-assembled patterning. Her interests include nano- to microscale communication networks by cellular machines and integrated cell-to-cell interactions for 3-D tissue organization and function. She is well published, has two information disclosure/patents pending, and has given numerous national and international presentations on her research. Her laboratory is at CNSE, which is one of the premier nanotechnology centers in the U.S. and the world.

Dr. Paluh is serving on the IEEE 1906.1 Standards Working Group on nanoscale networking. She is an Associate Editor of *F1000* and an Editor of the *Advances in Stem Cell Discovery* journal and was a Coeditor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS 2013 special issue.

Christopher Rose (S'78–M'86–SM'05–F'07) received the S.B., S.M., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 1979, 1981, and 1985, respectively, all in electrical engineering and computer science. He is currently a Professor of electrical and computer engineering at Rutgers University, North Brunswick, NJ, USA, where he is a member of the Wireless Information Network Laboratory, and where he served as the Associate Director from 1999 through 2007. He is also currently a member of the Army Science Board. Previously, he was a member of the Network Systems Research Department, AT&T Bell Laboratories. His current technical interests include novel communications networks, applications of genetic algorithms to control problems in communications networks, and interference avoidance methods using universal radios. His most recent interests—novel applications of communication theory—include such topics as communication within biological systems, communication theory, and supersymmetry and such nonstandard communication methods as inscribed matter transport. His latter work appeared in *Nature* as the September 2, 2004 cover article.

Prof. Rose is a Fellow of the IEEE cited for contributions to wireless system communications theory. His latter work with Sennur Ulukus and Roy Yates received the IEEE Marconi Prize Paper Award in Wireless Communications in 2003.