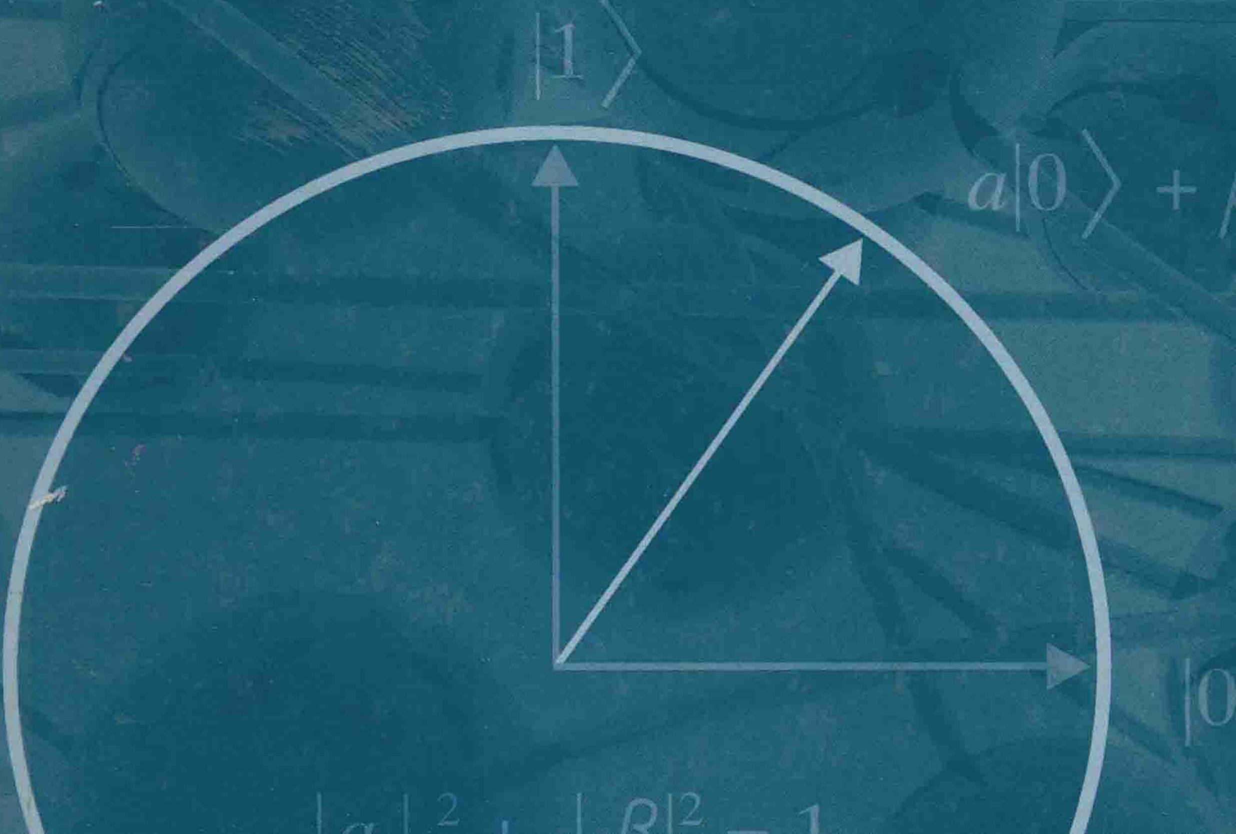
Nanoscale

# Communication Networks

Stephen F. Bush



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# Preface

## OBJECTIVE

Richard Feynman presciently stated in his 1959 talk that "There's Plenty of Room at the Bottom." I believe that within this vast room at the bottom there will be a requirement for communication. Think of entire networks, or at least network nodes, that are the size of today's bits. I am *not* referring to nanotechnology being applied to today's macroscale communication, but rather to entire network systems that exist at the nanoscale, with nanoscale "users" such as nanorobots and molecular machines. The relatively new field of nanoscale communication networking seeks to shrink network communication in size to the scale of individual molecules; this topic includes the goal of transmitting information where traditional communication has never gone, including inside the cells of living organisms. Physics, biology, and chemistry will play a much greater role in this form of networking compared to the traditional electronics to which most people are accustomed today. This book will prepare the reader for the convergence of nanotechnology and networking. My goal is to provide students and professionals with a rapid, easy way to become proficient without having to personally read the 1,000+ papers on this topic; a selected set of 271 comprise the bibliography.

## GENESIS

The idea for nanonetworks was inspired by a variety of sources, including early work on the effect of misalignment of carbon nanotubes within field effect transistors. Carbon nanotubes are a high mobility (rapidly switching) semiconductor. The idea was that the more we could reduce the requirement for perfect alignment among nanotubes, the cheaper and easier it would be to produce such transistors, assuming we could understand the impact of misalignment upon transistor performance. Once a certain degree of randomness in nanotube orientation was allowed, it was very compelling to think of the nanotubes as ad hoc Internet connections on a very small scale. Of course, this is only one of many possible approaches to nanonetworking as you will see in this book.

Through early conferences on this topic, such as the Nano-Networks conference series, other researchers thinking about diverse aspects of nanonetworking came together and formed the IEEE Emerging Technologies Committee on Nano-Scale, Molecular, and Quantum Networking.[1] I also introduced this topic as part of a general computer networking course at the State University of New York (SUNY) University at Albany campus; the students were intrigued by the concept and I owe them a debt of gratitude for providing the questions and enthusiasm to help build upon this topic.

1 http://www.comsoc.org/nano

## APPROACH AND CONTENT

Nanoscale communication takes many forms, and includes the concept also known as molecular communication. The term "molecular communication" is often used when the transmission media is biological in nature. I take a much broader view of nanonetworking as shown in the overview of the contents of the book in Figure 1. Dashed lines show alternative coherent paths through the chapters. I recommend reading Chapter 1 and then either following the chapters in numerical order, or choosing among Chapters 2, 3, 4, and 5, as they relate to the underlying media that most interests you. Chapters 6, 7, and 8 follow with material that is common to all nanoscale media. Note that Chapter 7 includes architectural concerns that can be media-specific.

This book is written for both the student and the professional. Both can benefit by exercising their knowledge with the problem sets at the end of each chapter. This facilitates use as a supplementary course textbook or as a book for professionals to quickly become acclimated to this new field. There is an extensive bibliography with more than 270 papers that were researched in the writing of this book; a bibliography is provided for each chapter. Solutions to the exercises, slides, and other addenda to the book will be provided at `www.comsoc.org/nano`.

We begin the book by defining the nascent field of nanoscale networking, looking at how it has come into existence, and examining the driving forces behind this new field within Chapter 1. The following four chapters concentrate on specific nanoscale media. Thus, Chapters 2 and 3 describe biologically oriented media; they focus upon molecular motor communication as well as gap junction communication and cell signaling, respectively. These areas are biologically inspired; it is a very diverse research field with collaborative research from the biological fields. The goal of this book is not to convert network researchers into biologists and quantum physicists, but rather, to provide enough conceptual background to allow network researchers to understand how biological systems can be leveraged to transport information. Chapter 4 focuses on carbon nanotube networks; it can be divided into two parts: a brief introduction to research into nanonetworks used as chip interconnects and then a stronger focus on research into nanonetworks (largely random nanotube networks), which goes beyond application to chip fabrication. This topic, like the biological nanonetworks just mentioned, is a very diverse and collaborative field, which includes not only computer science but computer engineering, physics, and many other fields. Chapter 5 addresses what is truly the ultimate in small-scale phenomena, quantum computation and communication. Quantum networking and quantum computation is a vast topic in its own right; I have had to make some difficult decisions in narrowing down the topic and introducing the concepts as concisely as possible.

By this point in the book, the topic of nanonetworking will have been well defined and various specific nanoscale media will have been explained. The next step is to discuss general techniques for analyzing such systems. First, in Chapter 6, I address information-theoretic aspects of nanonetworks. The information-theoretic aspects focus not only on traditional information and entropy applied to nanoscale systems, but also to relatively recent work on more unique aspects of nanoscale networking such as communication through diffusion and a brief introduction to quantum information. Then, in Chapter 7, architectural issues are discussed. Most readers are familiar with macroscale Internet layered communication protocol stacks and commonly accepted principles of network architecture. We consider how these principles change when we shrink entire networks down to the nanoscale. For example, the active network architecture [1] has been suggested by multiple researchers as a potentially more efficient architectural approach.

Because nanoscale networking is still a revolutionary field, there are very limited resources for simulation and analysis of nanoscale networks. The appendix attempts to address this problem by highlighting relevant research centers and tools that are likely to aid nanoscale network researchers. The appendix includes a review of several molecular simulation platforms in which simulation software can be used to test hypotheses about molecular communication.

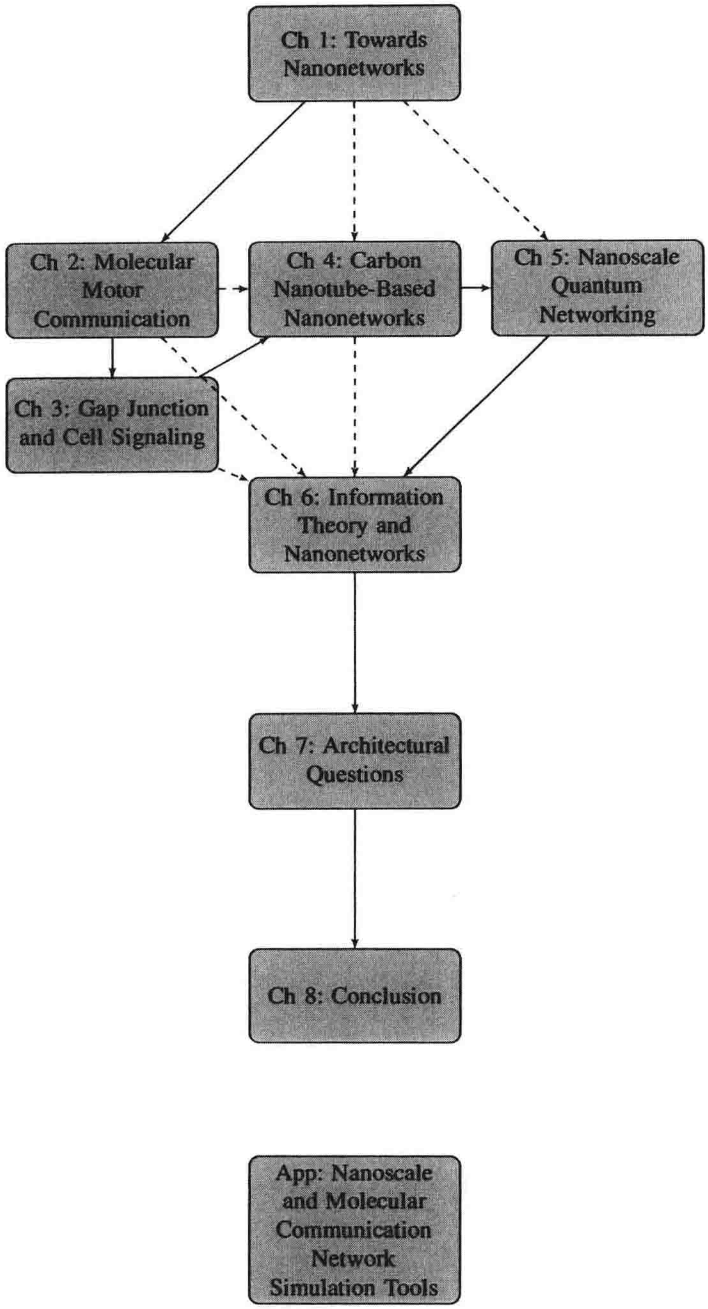


**Figure 1** Chapter dependencies for nanoscale communication networks.

# Acknowledgments

This book could not have come together without the expertise and mutual support of many dedicated researchers. I extend thanks to Imrich Chlamtac and Gian Maggio, and in particular to the folks involved in the International Conference on Nano-Networks, particularly in the Third conference (Nano-Net 2008). Alexandre Schmid did an outstanding job presiding over the review process used to select the papers to be presented at this conference. I am deeply grateful to the members of the Technical Program Committee for their tremendous effort in evaluating (along with many anonymous reviewers) the submissions and for organizing the papers into sessions, all on a tight schedule. I extend my deepest thanks to the organizing committee, in particular, Alexandre Schmid, as well as the active organizing members, namely, Sasitharan Balasubramaniam, Alexander Sergienko, Nikolaus Correll, Kaustav Banerjee, Radu Marculescu, and Tatsuya Suda. There were three outstanding plenary speakers in Tatsuya, Sylvain Martel, and Neil Gershenfeld, who gave inspirational speeches on a variety of truly fascinating topics regarding networking at the nanoscale. In the panel discussion on "Using Advanced Micro/Nano-electronic Technology to Establish Neuromorphic Systems," panelists Prof. Garrett Rose, Dr. Vladimir Gorelik, Prof. Eugenio Culurciello, Shih-Chii Liu, and Dr. Matthew Hynd shared their perspectives on this growing technology related to the formation of the ultimate nanoscale network, a brain-like system. Yun Li organized an excellent tutorial session for Nano-Networks 2008. I would like to extend my warm thanks to Wei Lu for stepping up to share his ideas and expertise with the community in the form of the first Nano-Network tutorial. Maggie X. Cheng has done an excellent job as publications chair. I also owe a special debt of gratitude to Sanjay Goel and Damira Pon of SUNY for an outstanding and highly professional job in organizing the Nano-Network Workshop and hosting the symposium web site. They responded to literally hundreds of requests for changes and updates to the Web site—all accomplished in a timely and efficient manner. I also extend thanks to Andrew Eckford who has done outstanding work in furthering the information theory aspect of nanonetworking.

# Contents

# Chapter 1

# Towards Nanonetworks

> Progress, far from consisting in change, depends on retentiveness. When change is absolute there remains no being to improve and no direction is set for possible improvement: and when experience is not retained, as among savages, infancy is perpetual. Those who cannot remember the past are condemned to repeat it.
>
> *George Santayana*

The goal of this chapter is to examine how the concept of nanonetworking has come into existence, to provide a proper definition for nanoscale networking, to outline some of the driving forces behind this new field, and finally to provide an introduction to the techniques required to advance this exciting field that will be used in the remainder of the book. Having defined the concept of nanoscale networking, it is important to understand the status and trajectory of today's technology and the challenges that will need to be overcome to implement the broader vision of nanoscale networking. As a preview of what is to come, Chapters 2 and 3 describe biologically oriented nanonetwork media. They will require basic knowledge of thermodynamics provided in this chapter and will focus on molecular motor communication as well as gap junction communication and cell signaling, respectively. Chapter 4 focuses on carbon nanotube networks; this will require basic facility with electronics, matrices, and eigenvalues. Chapter 5 addresses quantum communication and networking, which will assume the background provided in this chapter. Chapter 6 addresses information-theoretic aspects of nanonetworks; a basic introduction to the origin of information theory from physics is presented in this chapter. Chapter 7 addresses architectural issues including the notion of self-assembly; consideration is given to potential changes in today's commonly accepted networking principles when entire networks shrink to the nanoscale. All of the remaining chapters will assume at least a cursory understanding of the concepts introduced in this chapter. The reader is urged to attempt the exercises at the end of each chapter; many formulae and equations are explained throughout the text with the goal of mastering the exercises and ultimately being able to transition the material from a cursory understanding to actual analysis and application.

## 1.1 BRIEF HISTORICAL CONTEXT

An intersection of two worlds, emerging nanotechnologies and network and communication theory, is poised to change the nature of networking. New communication paradigms will be derived from the transition from micro- to nanoscale devices. The related degrees of freedom and constraints associated with these new technologies will change our notions about efficient networks, system design, and the nature of networking. Work is ongoing on a multidisciplinary front towards new techniques in modeling, design,

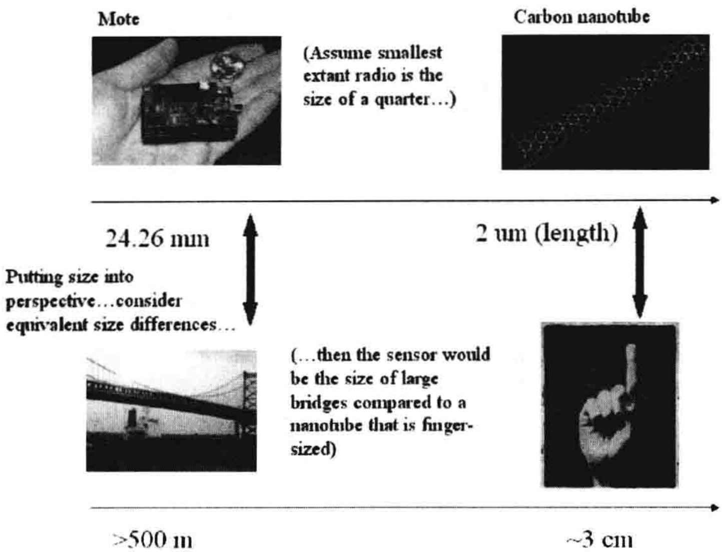


**Figure 1.1** Comparison of macro- and nanoscale networking. The size of a wireless mote sensor is to a nanotube as the length of a large bridge (or an Ethernet segment) is to a finger on the human hand.

simulation, and fabrication of network and communication systems at the nanoscale. This section reviews the state of the art and considers the challenges and implications for networking. As specific examples, consider three fundamental manifestations of nanoscale networks: (1) biological networking, (2) nanotube interconnections, and (3) quantum communication.

Networks communicating information already exist on a nanoscale [2]. Interconnected carbon nanotubes, micrometers in length, and nanometers in diameter, convey signals across areas of tens of square micrometers [3]. Wireless transmission and reception among components on a single chip have been designed in [4] and patented in [5]. Consider the impact of the extreme difference in scale between today's networks and nanoscale networks. In Figure 1.1 the size of a wireless mote sensor is to a nanotube as the length of a large bridge (or approximately an Ethernet segment) is to a finger on the human hand. Thus, it is clearly much easier to manipulate and replace components in today's Internet than at the nanoscale.

In terms of nanoscale sensor networks, the network components are on the same scale as the individual molecules of the sensed elements. Management of the complexity of such systems becomes significantly more difficult. The ability to detect and mitigate malicious behavior is thus more difficult. The problems are twofold: (1) the significant increase in the complexity of nanoscale systems due to their larger number of components within a compact space; (2) the mismatch in the size of the networking components, making them individually more difficult to detect and handle.

Solutions from macroscale wide-area networking are being proposed for use in on-chip networks. The implementations for the routers vary widely using techniques of packet or circuit switching, dynamic or static scheduling, wormhole or virtual-cut through routing. The majority of the current router implementations for network-on-chip (NoC) are based on packet-switched, synchronous networks. Some research has proposed an NoC topology and architecture that injects data into the network using multiple sub-NICs (network interface controllers), rather than one NIC, per node. This scheme achieves significant improvements in nanonetwork latency and energy consumption with only negligible area overhead and complexity over existing architectures. In fact, in the case of MESH network topologies, the proposed scheme provides substantial savings in area as well, because it requires fewer on-chip routers.

Another theme that drives research in on-chip networks is the likelihood that production of chips with massive numbers of processing elements and interconnections will increase uncertainty with respect to on-chip properties. Researchers following this theme begin to address issues that will also be of concern in the long-term for self-assembled systems. For example, some links might be so long that communications between processing elements cannot occur in a single clock cycle [6]. In other cases, chip properties might lead to transient, intermittent, or permanent communication errors [7]. Other research considers how to operate a chip when dimensions are so small as to preclude distribution of a reliable clock [8]. Such uncertainty leads researchers to propose various schemes for robust on-chip communications [9–11].

## 1.2 NANOROBOTICS

Another driver for nanonetworks has been nanorobotics, in which there are two major research thrust areas [12]. The first area deals with design, simulation, control, and coordination of robots with nanoscale dimensions. The second research area focuses on overall miniaturization of mobile robots down to micrometer overall sizes. Nanorobots, nanomachines, and other nanosystems are objects with overall dimensions at or below the micrometer range and are made of assemblies of nanoscale components with individual dimensions ranging approximately between 1 to 100 nm. In these mobile robotic systems, overall system size is very limited, which induces severe constraints in actuators, sensors, and motion mechanisms; power sources, computing power, and wireless communication capability. When scaling down, the surface-to-volume ratio increases and surface forces dominate volume-based forces. At nanometer scales, interatomic forces or surface chemistry plays a significant role in robot mechanics. Thus, inertial forces and weight are almost negligible and micro/nanoscale surface interatomic forces, fluid dynamics, heat transfer, surface chemistry, and adhesion-based contact mechanics and friction dominate robot mechanics. These micro/-nanoscale forces have many different characteristics compared to macroscale ones [13]. Our focus is on information transmission among such nanomachines [14] and whether nanoscale forces have an impact upon the fundamentals of communication. Research into nanorobotics is well under way [15].

## 1.3 DEFINITION OF NANONETWORKS

Nanonetworks are communication networks that exist mostly or entirely at the nanometer scale. The vision of nanoscale networking achieves the functionality and performance of today's Internet with the exception that node size is measured in nanometers and channels are physically separated by up to hundreds or thousands of nanometers. In addition, nodes are assumed to be mobile and rapidly deployable. Nodes are assumed to be either self-powered or "sprinkled" onto their target location. Individual nodes of such small size may seem too constrained to have any significant functionality. However, quite the opposite is true. The operation of molecular motors has appeared in a wide variety of contexts and with amazingly complex operation. Molecular motors will be discussed in great detail in Chapter 2. Most useful applications of nanoscale networking will require communication in environments where the nodes are in motion, for example, within the complex dynamic environment of living organisms or as nanoscale sensors or robots inspecting sensitive parts in an automated process. Communication should leverage the natural environment with as little disruption as possible.