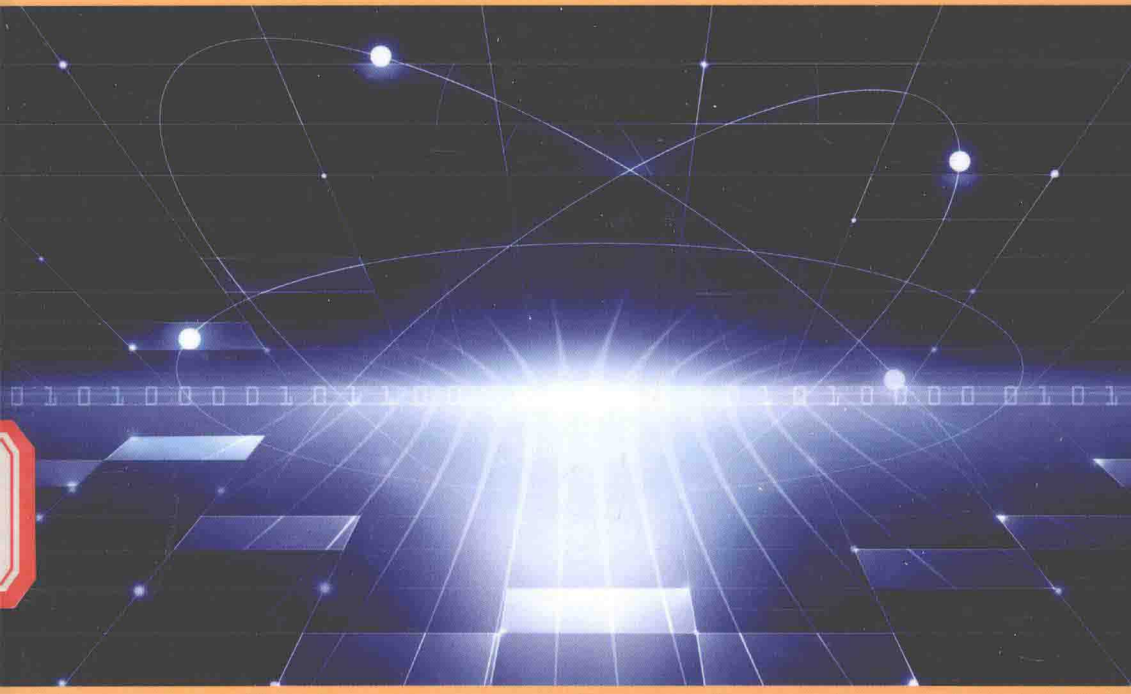
NETWORKS AND TELECOMMUNICATIONS SERIES

# Quantum Networking

Rodney Van Meter



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# Quantum Networking

Rodney Van Meter

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# Notations

| | |
|---|---|
| $\|0\rangle$, $\|1\rangle$ | Basis vectors for a qubit in the computational ($Z$) basis, written in Dirac's *ket* notation. |
| $\|+\rangle$, $\|-\rangle$ | Basis vectors for a qubit in the $X$ basis, written in Dirac's *ket* notation. |
| $A$, $B$ | Names of nodes; abbreviations for Alice and Bob. Nodes are referred to with a numeric address in some places. |
| $a$, $b$, $c$, $d$ | Diagonal elements of a two-qubit density matrix written in the Bell basis, corresponding to the probabilities of $\|\Phi^+\rangle$, $\|\Psi^+\rangle$, $\|\Phi^-\rangle$ and $\|\Psi^-\rangle$, respectively. |
| $a_{AB}$, etc. | Corresponding element of the d.m. of a two-qubit state (typically a Bell pair) shared between Alice and Bob. |
| $\mathbb{C}$ | The set of complex numbers. |
| $F$ | Generic for the fidelity of the state of one or more qubits, $F = \langle\psi\| \rho \|\psi\rangle$. $F = 1.0$ is a pure state. $F = 2^{-n}$ is the fidelity of a completely mixed state of $n$ qubits. |
| $l_0$ | Attenuation length in fiber. |
| $\|\psi\rangle$ | Dirac's *ket* notation for a state vector. Generic for the state vector of a pure state of one or more qubits. It may be either a physical qubit or a logical one encoded using quantum error correction, depending on the context. |
| $\left\|\widetilde{\psi}\right\rangle$ | Dirac's *ket* notation for a qubit encoded using quantum error correction; a logical state, as opposed to a physical one. |
| $\|\bar{\psi}\rangle$ | Dirac's *ket* notation for the NOT of a qubit. |
| $H$ | Usually, the single-qubit Hadamard gate; occasionally, the Hamiltonian representing the physical evolution of a state. |
| $P_b$ | Probability of success of the base-level physical entanglement operation. |
| $P_{p1}$ | Probability of success of the first round of purification. |
| $\mathcal{P}_0^1$ | Projective measurement operator for the value 0 on qubit 1. |

| | |
|---|---|
| $T_1^A$ | $T_1$ energy relaxation time, or bit flip decay time, of the qubit in a Bell pair held at node $A$ (Alice). |
| $T_2^A$ | $T_2$ (phase relaxation time) of the qubit in a Bell pair held at node $A$ (Alice). |
| $t_{\mathrm{L1}}$, $t_{\mathrm{LR}}$ | Link-level one-way latency, round-trip time. |
| $t_{\mathrm{E1}}$, $t_{\mathrm{ER}}$ | End-to-end one-way latency, round-trip time. |
| $X$, $Y$ and $Z$ | The single-qubit Pauli operators. Also written as $\sigma_X$, etc, in other texts and papers. |
| $\|\Psi^-\rangle^{(AB)}$ | A Bell pair with one qubit held by node $A$ and one qubit held by node $B$. |
| $\rho$ | Generic for the density matrix for one or more qubits. |
| $\rho_{AB}$ | Density matrix for a two-qubit state (typically a Bell state) shared between nodes $A$ and $B$. |
| $O(\cdot)$ | Asymptotic upper limit on growth in total number of computational operations, or execution time (circuit depth/algorithm steps) as problem size grows. |
| $\Theta(\cdot)$ | Exact asymptotic growth in total number of computational operations, or execution time (circuit depth/algorithm steps) as problem size grows. |
| $\Omega(\cdot)$ | Asymptotic lower limit on growth in total number of computational operations, or execution time (circuit depth/algorithm steps) as problem size grows. |

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# Acknowledgments

> As no better man advances to take this matter in hand, I hereupon offer my own poor endeavours. I promise nothing complete; because any human thing supposed to be complete, must for that very reason infallibly be faulty.
>
> Herman Melville, *Moby Dick*

I owe more than I can say to my wife Mayumi and daughters Sophia and Esther. They have been patient throughout the writing of this book, accepting, "Sorry, I have to work on the book", as an excuse for everything from missing a soccer match to skipping my share of the housework. I love you three beyond all words.

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Although I have benefited immensely from the advice of a number of people who are more expert than me in many of the subfields covered in this book, I bear the ultimate responsibility for the contents; any misrepresentations of history, let alone actual technical mistakes, are my own. Comments are welcome; in this digital age, the print form of the first edition of a book is hardly the last word. I look forward to hearing from you.

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– APARICIO L., VAN METER R., "Multiplexing schemes for quantum repeater networks", *Proceedings of the SPIE*, vol. 8163, pp. 816308, August 2011.

– APARICIO L., VAN METER R., ESAKI H., "Protocol design for quantum repeater networks", *Proceedings of Asian Internet Engineering Conference*, November 2011.

– VAN METER R., LADD T.D., MUNRO W.J., *et al.*, "System design for a long-line quantum repeater", *IEEE/ACM Transactions on Networking*, vol. 17, no. 3, pp. 1002–1013, June 2009.

– VAN METER R., TOUCH J., HORSMAN C., "Recursive quantum repeater networks", *Progress in Informatics*, no. 8, pp. 65–79, March 2011.

– VAN METER R., SATOH T., LADD T.D., *et al.*, "Path selection for quantum repeater networks", *Networking Science*, vol. 3, no. 1–4, pp. 82–95, December 2013.

– VAN METER R., HORSMAN C., "A blueprint for building a quantum computer", *Communications of the ACM*, vol. 53, no. 10, pp. 84–93, October 2013.

Some of the material appeared in my PhD thesis, "Architecture of a quantum multicomputer optimized for Shor's factoring algorithm," Graduate School of Science and Technology, Keio University, 2006.

Rodney VAN METER
Faculty of Environment and Information Studies
Keio University
March 2014

# Introduction

We are going to need a quantum Internet, and to build it, we need quantum internetworking technology. This book is my contribution to both the technical and social work of getting there. It is based on my experiences during 15 years of work on classical computing systems and networks, followed by a decade of research on quantum computing systems and networks.

Quantum information, including both quantum computing and quantum communication, is poised to have a large and sustained impact on the fields of theoretical and experimental quantum physics, theoretical computer science (or informatics) and ultimately the information technology industry. One important subfield is quantum networking, especially using *quantum repeaters*, which are the focus of this tome. Quantum signals are weak and very fragile, and, in general, cannot be copied or amplified. Engineering quantum communication sessions that can reliably exchange data over long distances, in topologically complex networks built on heterogeneous technologies and managed by many independent organizations, requires an extraordinarily broad range of expertise, which few individuals anywhere have *in toto*. Over the next 300 or so pages, we will attempt to lay a common foundation on which each person can erect his or her contribution.

The primary audience of the book is two-fold:

– computer networking folks with no prior background in quantum information, who are curious and considering working in the field;

– quantum information experts who have yet to work in the area of repeaters and need an introduction, or those who have begun working in the area but need more background in networks.

Ideally, the book will produce a "meeting of minds" between the two communities. Networkers will find that quantum networking is less intimidating than

it initially appears, and that there are breathtaking concepts underlying an emerging class of uses for distributed quantum information. Physicists will discover that networks are complex, artificial artifacts with emergent behaviors not immediately anticipated from the behavior of individual building blocks, and are built on some principles that are every bit as fundamental and beautiful as those they have been studying in physics. By the end of the book, readers from either community should be prepared to design a quantum repeater network, based on both classical network architecture and the existing literature on quantum repeaters. Readers should know enough to implement simulations of repeater networks that properly take into account (1) a reasonable abstraction of the physics, (2) the distributed, autonomous nature of decision-making and (3) the technical and operational heterogeneity of networks of networks such as the Internet.

The book is intended to be a readable introduction rather than a comprehensive, in-depth tome; each chapter is 10–20 pages, intended to be ingested in one sitting. Most chapters will use only basic linear algebra and probability theory. The approach emphasized throughout the book will be on the use of classical networking principles to build a sustainable, extensible, robust quantum repeater network architecture.

The overall flow of the book is an overview, three chapters on background (quantum information, networking concepts and teleportation), then three chapters on applications (QKD, distributed digital computation and entangled states as reference frames) to motivate the development of networking technology. In Part 3 of the book, the focus first shifts to the bottom of the stack, beginning with the physical entanglement experiments and link design. After working through purification, we come to the three major classes of communication session architecture for chains of quantum repeaters: the original entanglement swapping approach, the more recent error correction based approaches, and the recent work on asynchronous approaches. The book ends with a series of chapters on issues in multi-user, autonomous networks: multiplexing, routing and internetworking architecture, featuring the Quantum Recursive Network Architecture (QRNA).

The reader will find varying levels of mathematical and logical rigor in different chapters. In particular, a thorough discussion of physical implementations would fill a separate book, which we leave to the physicists. Likewise, at the highest level, the details of the security protocols and proofs for applications such as verifiable secret sharing are beyond the scope of this book; the applications are presented in just enough depth that casual readers will be able to understand why they are valuable, and what demands they make on the network itself.

Readers are assumed to be familiar with basic vector and matrix addition, multiplication and calculation of the determinant; exponentiation of matrices; complex numbers, including their exponentiation; and discrete probability. The mathematics presented here does not go beyond this level. Thus, although the

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concepts presented here are largely unfamiliar, abstract and sometimes counter-intuitive, the math itself is generally not particularly difficult. Chapter 2 includes explicit, worked examples of many of the mathematical principles. It is even possible for well-prepared first- and second-year undergraduates to work through the book.

For the advanced researcher, it is worth noting that this book lies halfway between the research monograph and the textbook on the spectrum. In the course of writing what I thought would be a relatively cut-and-dried presentation of some basics viewed from the point of view of a network engineer, I discovered a number of things that simply have not yet been done in the literature. Among them:

– distributed density matrix management (section 8.5);

– the "valley fold" timing for quasi-asynchronous repeaters (section 12.1);

– a moderately detailed analysis of network workloads imposed by applications of repeaters (Chapter 6);

– extended state machine-based designs for protocols.

Each of these likely will be a journal paper, perhaps more or less concurrent with the appearance of the book, but all but the last had their genesis in this writing project. (We began the state machine approach in a conference paper [APA 11b], but the book contains new material.) Each of these topics also deserves yet more attention than I have so far been able to give. I look forward to handing them off to my capable collaborators.

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