Quantum Computing and Quantum Communication

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INTRODUCTION

Quantum computing and quantum communication are based on quantum physics. Information is represented by quantum states defined by energy levels of molecules, atoms, and photons. Quantum information technology includes quantum computers, other quantum information processing devices, quantum programming methodologies, and quantum communication applications such as quantum key distribution systems and quantum signatures. Error correction is a necessary quantum information technology property because of high error vulnerability caused by quantum physics characteristics. This article presents state-of-the-art and future perspectives of quantum computing and communication.

BACKGROUND

Feynman's (1982) observation, that a classical computer cannot efficiently simulate the stochastic parallelism of quantum states, started research on using quantum mechanical effects for efficient information processing. Operating principles and implementation possibilities of quantum computing were outlined in Oxford University (Deutsch, 1985).

Bennett and Brassard (1984) proposed a quantum protocol, BB84, for perfectly secret information transfer. Efficient quantum algorithms, for example integer factorization (Shor, 1994) and unsorted search (Grover, 1996), were proposed. BB84 has been used for distribution of symmetric encryption/decryption keys (Quantum Key Distribution, QKD) in research networks (Elliot, Pearson, & Troxel, 2004; Quellette, 2004; Poppe, Momtchil, & Maurhart, 2008). Commercial QKD technology has been available over 10 years. Quantum digital signatures have been proposed and experimentally verified (Gottesman & Chuang, 2001; Lu & Feng, 2005; Clarke et al., 2012).

Small scale quantum circuit based computers have been built and successfully tested in research laboratories (Vandersypen et al., 2001; Monz et al., 2011). Since 2011 large scale commercial adiabatic quantum computers (Das & Chakrabarti, 2008) are available.

Achievements in quantum computing and quantum communication from 1970 till October 2015 are listed in (Timeline, 2015). Universities engaged in research and education on this topic are for example (qis.mit.edu, 2013; …from Quantum, 2011; mathQI, 2015; Quantum, 2015a; Quantum, 2015b)

INFORMATION REPRESENTATION WITH QUANTUM STATES

Two quantum states, for which a state transition exists, can represent a bit called a quantum bit or qubit, if the energy level of both states is measurable. However, quantum states are probabilistic. A measured energy level is one of several possi-

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bilities. Each possible outcome has a probability. The sum of all possible outcome probabilities is of course 1.

The *No Cloning* qubit property is the impossibility to clone an unknown quantum state. However, *Teleportation*, which changes the original qubit state, can transfer also an unknown quantum state.

Mathematical Treatment of Qubits

A qubit representation is a 2-dimensional vector. The orthogonal base vectors $(1,0)^T,(0,1)^T$ in *Dirac notation* $|0>,|1>$ represent binary values 0,1.

A qubit is a concurrent superposition of $|0>,|1>$. A measurement outcome is $|0>$ or $|1>$. In a qubit

$$|\psi>=a\cdot|0>+b\cdot|1>. \tag{1}$$

a,b are complex numbers and

$$<\psi||\psi>=(a^*,b^*)\cdot(a,b)^T=a^*\cdot a+b^*\cdot b=|a|^2+|b|^2=1. \tag{2}$$

$\{a^*,b^*\}$ are complex conjugates of $\{a,b\}$. $\{|a|^2,|b|^2\}$ are measurement probabilities of $|0>,|1>$.

Multiple Qubits

A *2 qubit* quantum state is a 2^2 component column vector. For

$$|\psi_1>=a\cdot|0>+b\cdot|1>,\ |\psi_2>=c\cdot|0>+d\cdot|1> \tag{3}$$

the state is

$$|\psi_1\psi_2>=|\psi_1>\otimes|\psi_1>=a\cdot c\cdot|00>+a\cdot d\cdot|01>+b\cdot c\cdot|10>+b\cdot d\cdot|11>. \tag{4}$$

$\otimes$ is the *tensor product*. $|00>=|0>\otimes|0>=(1,0,0,0)^T$, $|01>=|0>\otimes|1>=(0,1,0,0)^T$, $|10>=|1>\otimes|0>=(0,0,1,0)^T$, and $|11>=|1>\otimes|1>=(0,0,0,1)^T$ are the *base vectors*.

A *N qubit* quantum state $|\psi_1\psi_2\ldots\psi_N>$ is a superposition of 2^N base vectors. For a 3 qubit state $|\psi_1\psi_2\psi_3>$ the base vectors are $\{|000>,|001>,|010>,|011>,|100>,|101>,|110>,|111>\}$, where $|001>=|0>\otimes|0>\otimes|1>=(0,1,0,0,0,0,0,0)^T$, etc.

The state $|\psi_1\psi_2\ldots\psi_N>$ is *entangled* if no $|\psi_1>,|\psi_2>,\ldots,|\psi_N>$ exist for which $|\psi_1\psi_2\ldots\psi_N>=|\psi_1>\otimes|\psi_1>\otimes\ldots\otimes|\psi_N>$.

Example: $(1/\sqrt{2})\cdot(|00>+|11>)$ is entangled.

Proof: $(a\cdot|0>+b\cdot|1>)\otimes(c\cdot|0>+d\cdot|1>) = a\cdot c\cdot|00>+a\cdot d\cdot|01>+b\cdot c\cdot|10>+b\cdot d\cdot|11> \neq (1/\sqrt{2})\cdot(|00>+|11>)$, since one of $\{a,d\}$ must be 0.

Physical Implementation of Qubits

Qubits have been implemented by photon states, ion traps, cavity quantum electrodynamics (QED), nuclear magnetic resonance (NMR), quantum dots, superconducting circuits, and in silicon (Nielsen & Chuang, 2002; Devoret & Schoelkopf, 2013; Veldhorst et al., 2015).

A physical qubit property is decoherence time, during which a qubit state is maintained before collaps caused by interaction with the physical environment.

A qubit implementation in quantum communication is a photon *polarization state* consisting of all propagation planes of the electromagnetic wave of the photon. A random polarization is a superposition of an orthogonal state pair. Orthogonal state pair examples:

- Horisontal and vertical polarization.
- +45° and -45° diagonal polarization.

A photon polarization state is thus a qubit

$$|\psi>=a\cdot|horis>+b\cdot|vert>=c\cdot|+45°>+d\cdot|-45°> \tag{5}$$

a,b,c,d are complex numbers and $|a|^2+|b|^2=|c|^2+|d|^2=1$. One state in a chosen pair must be interpreted as $|0>$, the other as $|1>$. Pho-

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