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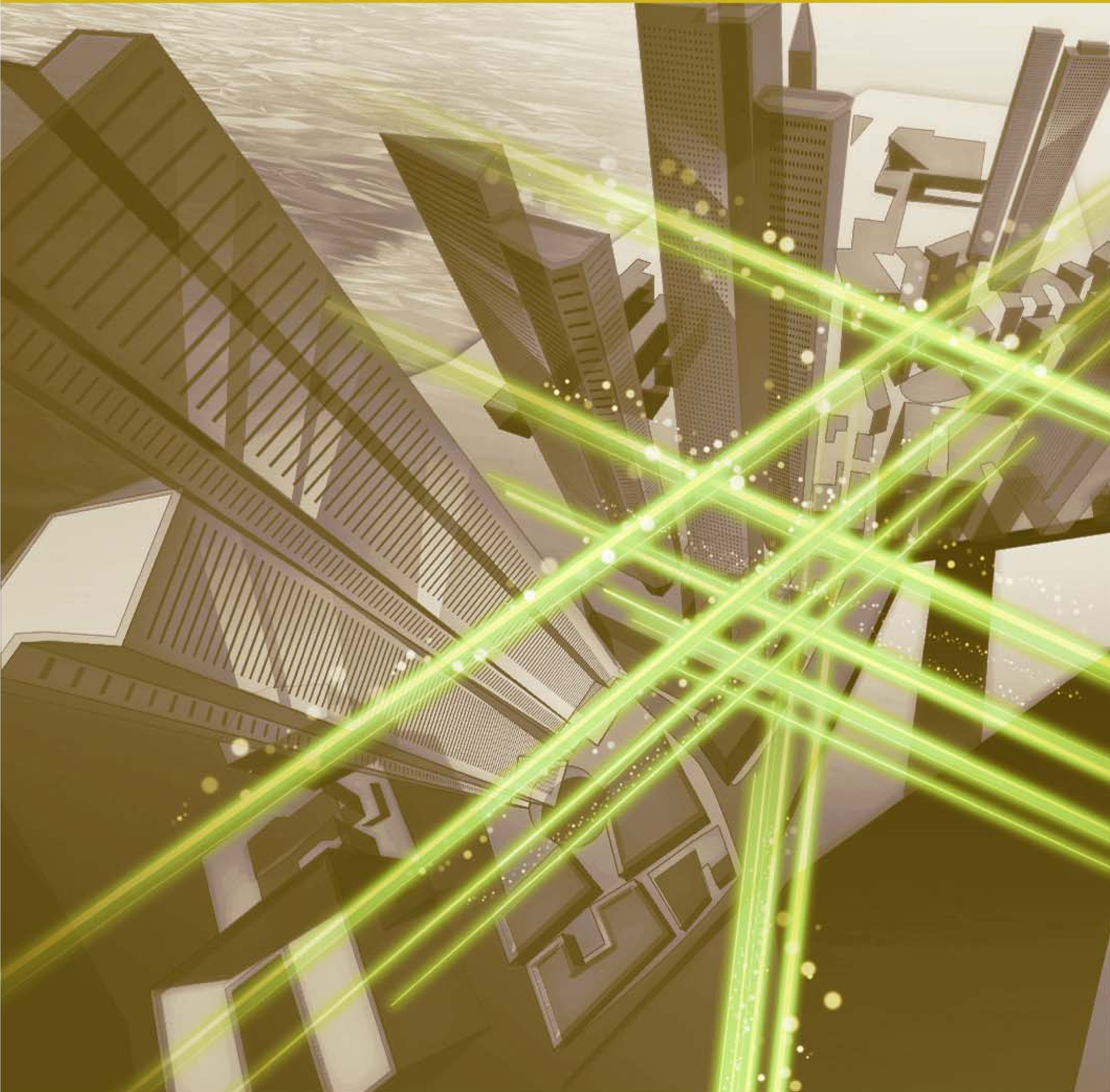

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The Arrival of a New Era in Quantum Information Processing Technologies

Hiroshi Yamaguchi and Tetsuomi Sogawa

Abstract

Research on quantum information processing has progressed astoundingly in the past several years. Concepts totally different from before such as adiabatic computation, quantum measurements, and topological states have been introduced, expanding the possibility of applications. This article introduces recent developments in quantum information processing and discusses NTT's research achievements as examples of the advances in this field.

Keywords: quantum information processing, quantum computing, quantum key distribution

1. Introduction

In the last ten years, the application of quantum information processing technologies has expanded to areas outside of our own field of specialty. In our work, we are often asked about quantum computing by non-specialists. When we began research on quantum technologies at NTT, we had to start by answering the question, "What does 'quantum' actually mean?" Now, however, we are more often asked, "I know the background story. How far have you progressed?" There have been times when news about quantum information processing would suddenly pop up when we were watching television or listening to the radio. When watching science-fiction movies, we would be surprised when a character suddenly uttered a line about "quantum teleportation." It seems that the subject of quantum information processing technologies has already spread widely from the realm of specialists to the general public.

NTT's research on quantum information processing goes back more than 30 years. We joined NTT about 30 years ago, and it is no exaggeration to say that our research career has unfolded alongside the development of quantum technologies in the NTT laboratories (NTT Labs). When research began at NTT, the usual answer to the question about when quantum computers would be put to practical use was "at least 30 to 50 years." Initially, quantum computing technologies were immature, and we think they gave the impression at the time that although the field was interesting theoretically, putting the technologies into practical use was not a simple matter.

However, astounding progress has been made in quantum computing over the last several years. When we first began our research, we had, in all honesty, a negative assessment of the possibility of practical quantum computing. When we look at the state of affairs now, however, we seriously think that it just might be possible that it will be used. Five years ago we contributed an article on quantum computing to the NTT Technical Review [1]. Re-reading the article again, we are struck by how far the field has advanced since then. In the US and Europe, world-famous companies have made large investments in the research and development (R&D) of quantum information processing technologies. It is truly an unexpected state of affairs.

How, specifically, has quantum computing progressed? The Feature Articles in this issue present the advances in this field. While one cannot understand all the latest quantum information technologies in 30 minutes just by reading these articles, we think one can understand the atmosphere in which these amazing technologies are continually developed based on new concepts. As a foreword to this issue, we wish to give an overview of these technologies and explain the new ideas behind them.

2. Adiabatic computation

It can be said that a major impetus of quantum computing research was the effort to achieve high-speed factorization to break RSA (Rivest-Shamir-Adleman) cryptography. This claim actually demonstrates the weakness of quantum computing. That is, the mention of factorization indicates that the problems that can be solved at a high speed by quantum computing are very limited. The number of proven high-speed algorithms, including those for simple and trivial problems, is extremely small. Consequently, no matter how much improvement there is in hardware development for quantum computing, it is unlikely that quantum computers will entirely replace the all-purpose personal computers we have today.

We refer here to the conventional method of quantum computation as *quantum gate computation*. In quantum gate computation, the solution to a problem is obtained by writing bit information to quantum bits (qubits) and then performing gate operations on them sequentially (called *unitary transformation* in quantum mechanics). This method is similar to the sequential computation carried out in computers today. While this is an easy-to-understand concept, bit information written in qubits must be correctly maintained and operated at all times. Thus, scaling up current hardware is not a simple matter.

In contrast to this approach, a computation method based on a completely different concept called *adiabatic quantum computation* has been proposed. In this concept, gate operations are not performed on each bit sequentially. Instead, the necessary answer is finally obtained by continuously changing the bit environment that makes up the computer (such as how bits are connected to each other). One of the biggest advantages of this method is its approach to perform calculations while constantly maintaining the lowest energy state.

The conventional gate computation approach involves the use of a high-energy excited state, and computational errors are produced by the transition to a low-energy ground state. Imagine quantum gate computation as passing a golf ball from person to person in a spoon relay. If there is just one little mistake, the golf ball falls to the ground. In other words, the computation fails.

In contrast, adiabatic computation continues in the manner of a soccer ball being kicked from person to person at ground level, where it cannot fall down. As a result, computation can be carried out without losing energy (called *energy relaxation* in technical terminology) (**Fig. 1**).

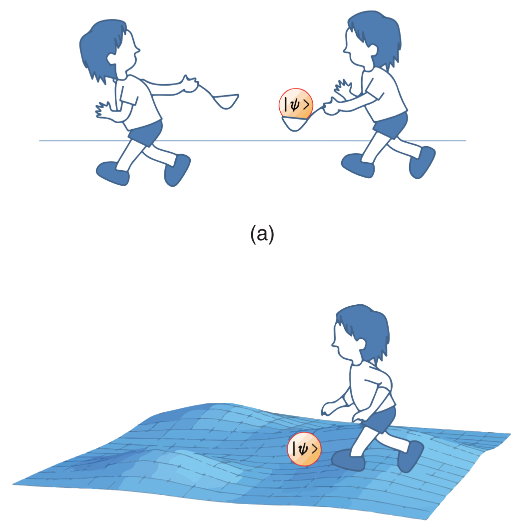
Another major advantage of adiabatic computation is that it can be applied to more problems than quantum gate computation. Although rigorous proof of its high-speed processing capability remains a future topic of research, adiabatic computation has been proposed as a method for handling many combinatorial optimization problems such as the traveling salesman problem and the knapsack problem, for which conventional computers require computation times that are exponential to the complexity of the problems.

The classical approach of obtaining a solution by changing the system while maintaining the lowest energy state—called simulated annealing—actually already exists. The proposed application of this method to quantum mechanistic conditions is called quantum annealing [2]. D-Wave Systems, a Canadian company, made news when it offered a commercial quantum computing product utilizing this approach. A joint research team that includes NTT Labs recently developed a quantum neural network that carries out the annealing using laser and optical fibers, and demonstrated a 2000-node calculation [3]. Although the use of an approach different from quantum annealing and the detailed roles of quantum mechanical superposition states should be clarified in the future, the experiment confirmed the high-speed capability (compared with the conventional computation) to solve a combinatorial optimization problem.

3. Quantum sensing technologies and experimental verification of quantum mechanical principles

As introduced in past articles of the NTT Technical Review, NTT Labs have developed various qubits to create quantum computers. Research on these qubits was conducted with multiplexing and circuit integration in mind and the assumption that in the future, it will be necessary to connect many qubits—several thousands and tens of thousands or more. The reason that developing a quantum computer is reportedly difficult is that it is not a simple matter to integrate such a large number of qubits.

However, there have been recent efforts to pioneer technologies that apply quantum computing without



(a)

(b)

Fig. 1. Pictorial representation of (a) conventional quantum gate computation and (b) adiabatic quantum computation. Gate computation is similar to a spoon relay race. Superposition states in qubits (|ψ> in the figure) are manipulated on sequentially. Because a high-energy excited state is used, calculations are not possible if error (energy relaxation) occurs when the ball is inadvertently dropped. The adiabatic computation (b) is equivalent to dribbling a ball while weaving through the dips in the ground. Computation is performed while constantly passing through the bottom of energy distribution.

using qubits or by using a small number of qubits. Until now, a linear progression of R&D was assumed for quantum information processing technologies. First, the problem of quantum key distribution would be tackled, and when that was successfully solved, the next step would be to tackle quantum computing. Integrating many qubits is essential in this linear development map.

However, nowadays there is growing awareness that quantum technologies can be used for a variety of goals that can be achieved with fewer qubits (**Fig. 2**). Quantum sensing technology is a representative example. The application of the superposition principle in quantum mechanics means that sensing technologies that are orders of magnitude higher in sensitivity than current technologies can be created. This technology exploits the strong interaction between qubits (the so-called quantum correlation) to create a state that is very sensitive to changes in the external environment.

Meanwhile, technologies to manipulate the quantum state and read it accurately have made great strides as a result of advances in quantum computing technologies. A new development is the use of these technologies to experimentally verify the principles of physics. In the past, because technologies to manipulate and detect quantum states were insufficient, it was impossible to experimentally answer questions involving the nature of physics, such as "To what size of objects can quantum mechanics be applied?" However, the technology has recently advanced to the point where accurate experiments could be carried out. In these Feature Articles, we introduce research on superconducting quantum circuits, which are applied to quantum sensing and the experimental verification of physical principles [4, 5].

4. Quantum cryptography and single photon manipulation

Quantum cryptography is a quantum information processing technology that is often discussed together with quantum computing. This technology is properly referred to as quantum key distribution. Rather than being an encryption technology, it provides solutions to everyday issues in encryption technology such as how to safely deliver a private key to the user. Disturbing a pure quantum state is an intrinsic part of the action of observing the state and cannot be avoided. Quantum key distribution secures the safe delivery of private keys by exploiting the fact that an act of

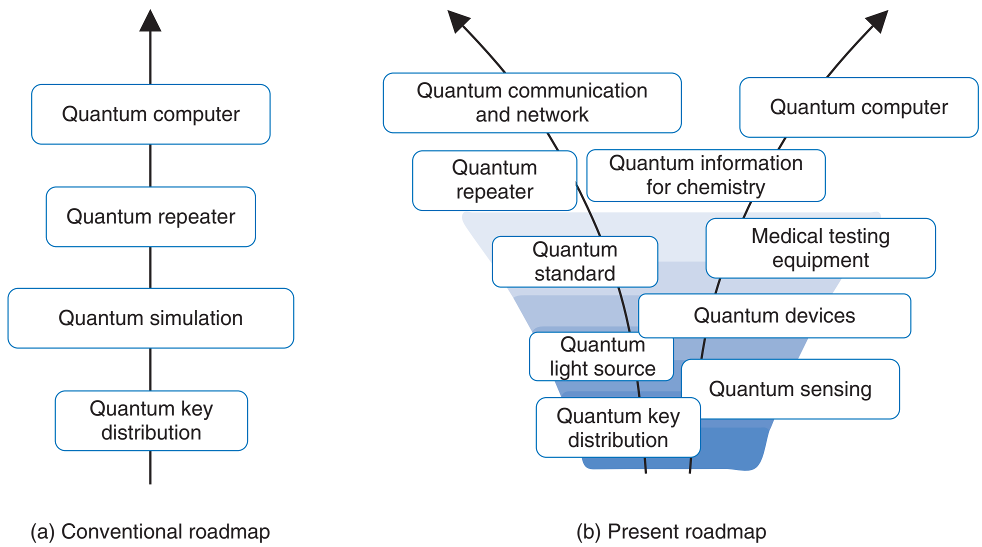


Fig. 2. Schematic showing the new expansion of quantum information processing. (a) The conventional roadmap shows a linear progression with the final goal of realizing quantum computing. (b) The current roadmap holds promise for the application of quantum technologies to a variety of fields, from quantum sensing to diagnostic tools.

eavesdropping during the stage of key distribution leaves an effect that cannot be fundamentally erased.

Compared with quantum computing, the prospects of quantum cryptography as a practical technology have always abounded, and in fact, experiments using optical fiber networks are being conducted in countries throughout the world. Although the technology is expected to be commercialized soon, there are still many challenges that must be solved, such as security proofs and the development of quantum repeater technologies. In this issue, we give an overview of the current state of quantum cryptography and challenges in its commercialization [6].

In addition to quantum cryptography, single photon generation technology also plays a critical role in quantum measurement and quantum computing. Quantum computing requires multiplexing. Thus, while the idea of manipulating a single quantum (photon) may sound contradictory, the question of to what extent each quantum can be manipulated with fine control is critical to carry out multiplexing in the future. Technology to finely control a single quantum (photon) is extremely important because a few quantum states play a critical role in quantum key distribution and quantum repeater technologies.

In this issue, we introduce the results of successfully controlling a wavelength of a single photon, which plays an important role in quantum information processing technologies. We accomplished this by applying the technique of cross-phase modulation, which is widely used in the field of optical communications, to a single photon for the first time [7].

5. Development of topological materials for quantum information processing

Finally, we touch on material research for topological quantum computers. The Nobel Prize in Physics in 2016 was awarded to three theoretical physicists at American universities for their theoretical discoveries of topological phase transitions and topological phases of matter. Topology is a discipline that seeks to understand the conditions of an object from the *connection* of things. Consider, for example, four shapes: a ball, coffee cup, donut, and wine glass. In topology, the size and curvature of a shape is not important. What is important is how connections are made. A coffee cup can be transformed into a donut by continuous deformation, as can a wine glass into a ball. However, to transform a donut (or coffee cup) into a wine glass (or ball), deformation of the former object by filling in its penetrating hole must be carried out somewhere. At this stage, the manner in which things are connected changes (**Fig. 3**).

In this way, it is known that different connection states, in other words, different topological states, appear not only in physical objects but also in a variety of physical systems. Electronics is a representative

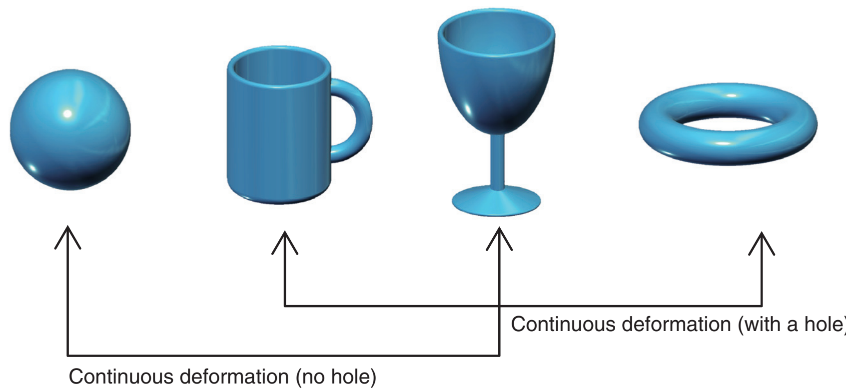


Fig. 3. Conceptual representation of topology. The ball and wine glass have completely different shapes. However, because they are connected through continuous deformation, they have the same topology. The cup and the donut have the same relationship. However, to transform the donut into the ball, for example, the penetrating hole in the donut must be filled in. Thus, it has a different topology, as it cannot be continuously deformed.

example. The Nobel Prize mentioned above demonstrates the extremely important role that electron states with different topologies play in solid-state physics. If it is possible to carry out quantum computing using such states, stable and highly accurate calculations can be performed since changes between different topological states do not occur easily.

Research on topological insulators applying the above findings has increased markedly in recent years. A topological insulator is a material in which electronic states with different topologies naturally manifest themselves due to the material's special properties. The heterostructure of two materials, indium arsenide (InAs) and gallium antimonide (GaSb), has attracted attention as an example of a topological insulator. NTT Labs have pioneered a method of crystal growth that dramatically improves the characteristics of this material. In this issue of the NTT Technical Review, we introduce the details of this research and discuss future prospects [8].

6. Conclusion

This article presented an overview of recent developments in quantum information processing and discussed NTT Labs' research achievements as examples of advances in this field. As mentioned in the Introduction, the progress in research on quantum information processing in the past several years has been astounding. New concepts such as adiabatic computation, quantum measurements, and topological states have been introduced, expanding the possibility of applications as a result of approaches that differ from conventional methods. In particular, while the adiabatic method has aroused debate about the extent to which quantum properties can be exploited in actual hardware, its future development is drawing attention because it solves computation problems with architecture different from the conventional computation architecture that uses quantum gates.

The most important properties of conventional digital computers are accuracy, which is achieved with binary encoding, and versatility, which is achieved with software. Originally, continuous analog values were encoded as digital information. Although inaccuracies generated in this process are ignored, calculations after encoding are executed without any mistakes. Also, the specifications of computation could be freely changed with software instead of being fixed in hardware. Present-day information processing technology has developed greatly based on the completeness and versatility of such a computational approach. However, we think the situation is gradually changing with the spread of the internet and the arrival of the big data era.

In the area of search technology, for example, how important is it to get a unique and rigorous answer to a search query? Rather, what is important is getting answers as quickly as possible from an extremely large number of choices in exchange for a modest level of certainty. In this way, adiabatic computation, which solves specific combinatorial optimization problems, has the possibility of truly being a powerful computing tool for a particular type of fuzzy problem. In this sense, the new technologies introduced here not only possess high-speed performance by exploiting quantum properties, they also have the possibility of changing how information processing technologies are fundamentally used.

Finally, while not introduced here, we would like to mention that great progress has also been made in the research on conventional gate model quantum computing hardware. We cannot predict which model of quantum information processing technology will change the world in the future, but we definitely wish to experience such a world beyond our wildest expectations.

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Quantum Neural Network for Solving Complex Combinatorial Optimization Problems

Hiroki Takesue, Takahiro Inagaki, Kensuke Inaba, and Toshimori Honjo

Abstract

Optimization of various social systems, including communication, traffic, and social networking systems, requires the solving of complex combinatorial optimization problems. In this article, we describe the recent progress achieved in developing a quantum neural network, a computer that finds solutions to combinatorial optimization problems using a network of degenerate optical parametric oscillators.

Keywords: Ising model, combinatorial optimization problem, optical parametric oscillator

1. Introduction

As various systems in our society grow larger and more complex, it becomes increasingly important to analyze and optimize such systems. These complex problems are classified as combinatorial optimization problems, which cannot be solved efficiently with conventional digital computers.

It is known that such problems can be converted to ground-state-search problems of the Ising model, which is a theoretical model proposed by E. Ising that describes a group of interacting spins. Several institutions recently reported artificial spin networks that were applied to simulate the Ising model in order to solve combinatorial optimization problems [1, 2]. Our team has been studying such an Ising-type computer called a quantum neural network (QNN) [3]. In a QNN, Ising spins are represented by degenerate optical parametric oscillators (DOPOs), which are coupled with mutual injections of DOPO light. In this article, we describe the basic working principle of a QNN and report the recent experimental progress made in this area at NTT.

2. Ising model

The Hamiltonian of the Ising model is given as follows.

$$H = -\Sigma_{i<j} J_{ij} \sigma_i \sigma_j. \qquad (1)$$

Here, σ_i and J_{ij} respectively represent the ith spin state and the coupling coefficient between the ith and jth spins. The ground state of the Ising model corresponds to a set of spins $\{\sigma_i\}$ that minimize Eq. (1) for a given matrix $\{J_{ij}\}$. A QNN, also known as a coherent Ising machine, is a network of artificial spins based on quantum optical oscillators that simulates the Ising model [3]. In our QNN, a spin state is represented by a DOPO, and the spin-spin interaction coefficient J_{ij} is implemented by adjusting the length and transmittance of an optical path between the ith and jth DOPO (**Fig. 1**). Since the networked DOPO tends to oscillate with a phase configuration that minimizes the total energy, we can obtain the ground state of a given Ising model by simply reading the phases of the DOPOs that are above the threshold.

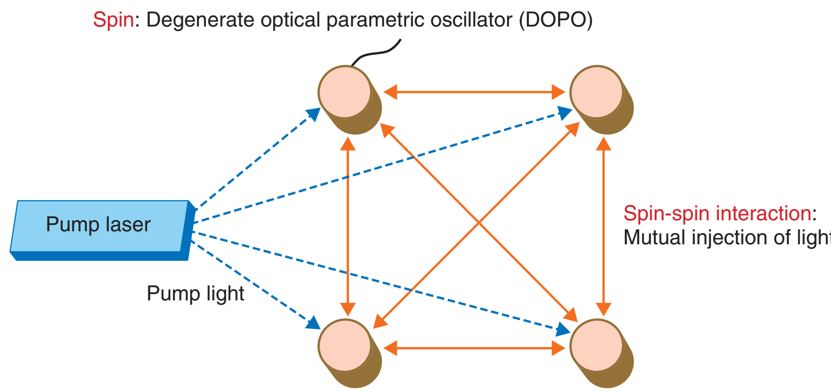


Fig. 1.   Concept of quantum neural network (QNN).

3. Phase sensitive amplification

An important physical phenomenon for generating a DOPO is a nonlinear optical effect called phase sensitive amplification [4]. When we input a pump light (angular frequency ω_p) and a signal light ω_s to a medium with the second or third order optical nonlinearity, we can generate an idler light with an angular frequency $\omega_i = \omega_p - \omega_s$ (second order case) and an initial phase $-\theta$, where θ represents the initial phase difference between the pump and the signal. In particular, when the signal and idler frequencies degenerate ($\omega_s = \omega_i$), the amplification coefficient of the signal amplitude is proportional to $\cos\theta$, which means that the light is efficiently amplified when its initial phase difference from the pump is either 0 or π.

To achieve such a phase sensitive amplifier (PSA), we can utilize four-wave mixing in an optical fiber [5, 6] or parametric down-conversion in a periodically poled lithium niobate waveguide [4, 7]. If we pump a PSA placed in an optical cavity, the 0- or π-phase component of the spontaneous emission noise is most efficiently amplified by the PSA, which eventually leads to an optical parametric oscillation with either one of the binary phase states (**Fig. 2**). In addition, if we use a pulsed pump whose temporal interval is set at $1/N$ of the cavity round-trip time, we can generate N time-multiplexed DOPOs using a single cavity.

We succeeded in generating more than thousands of DOPOs using a 1-km fiber cavity, paving the way towards achieving a large-scale QNN [5–7]. More recently, we reported the generation of more than 1 million DOPOs using a 10-GHz clock pump and a 20-km fiber cavity [8].

We can implement couplings between time-multiplexed DOPOs by inserting delayed interferometers. In an experiment reported in an earlier paper [6], we implemented nearest-neighbor coupling between DOPOs by placing a 1-bit delayed interferometer in the fiber cavity so that we could realize a one-dimensional Ising model. With the optically coupled DOPOs, we successfully observed that the DOPOs showed ferro- and antiferromagnetic behavior when we changed the phase difference between the two arms of the interferometer, suggesting that the DOPOs well simulated the characteristics of low-temperature spins.

4. Measurement-feedback scheme

The above one-dimensional Ising model experiment was important for understanding the physics of a QNN. However, it is difficult to solve real-world combinatorial optimization problems that are usually represented by large and complex spin networks using an optically coupled DOPO network. For example, in order to achieve all-to-all connection between 2000 DOPOs, we need as many as 1999 interferometers placed in the cavity, which is very hard to do experimentally.

We employed the measurement-feedback scheme shown in Fig. 2 in order to achieve flexible couplings among thousands of DOPOs. In this scheme, we measure the amplitudes of all N DOPOs $\{c_i\}$ while the DOPOs are circulating in the cavity and while controlling the evolution of their amplitudes. The measurement results are fed to a field programmable gate array (FPGA), where the spin-spin coupling matrix $\{J_{ij}\}$ for a given problem is set in advance. In each DOPO circulation in the cavity, the FPGA calculates

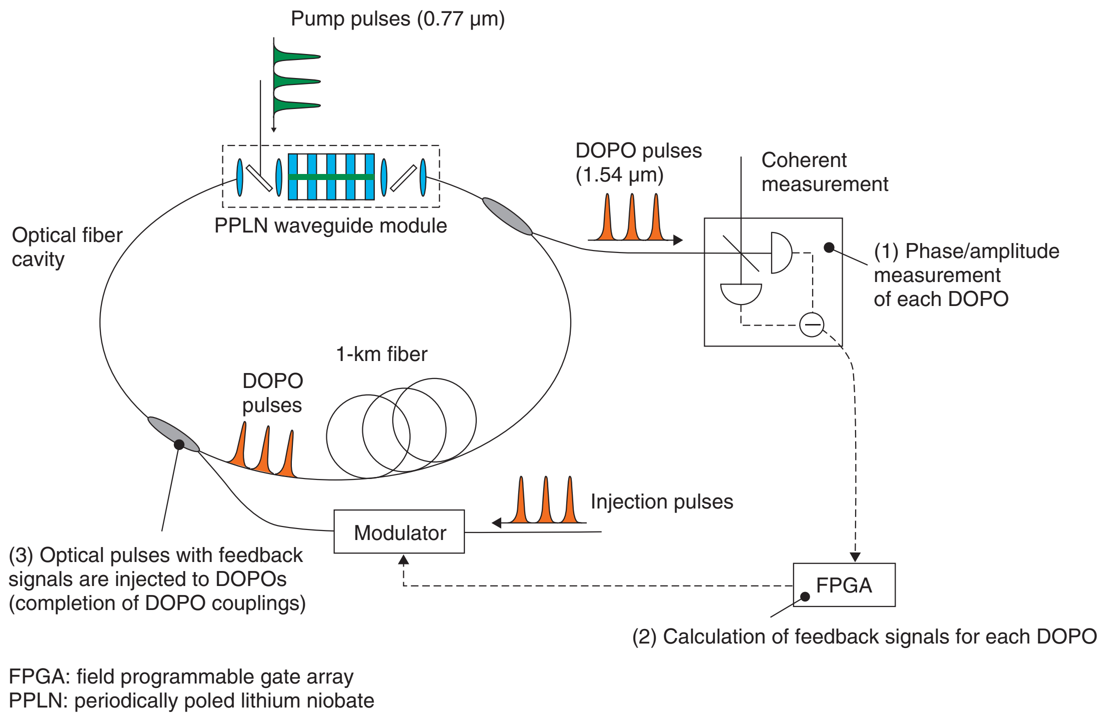


Fig. 2. QNN configuration.

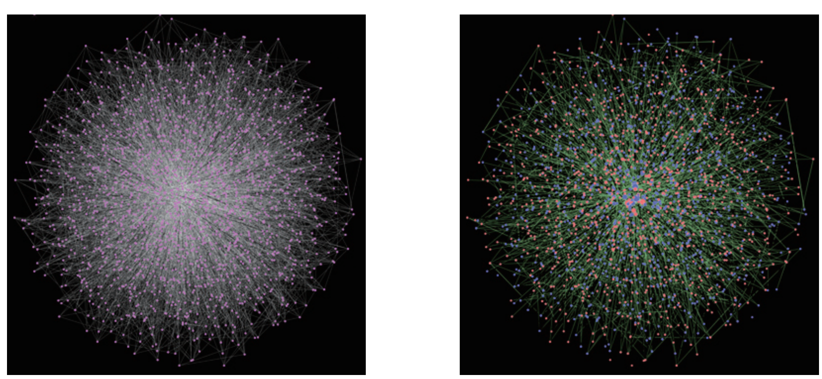
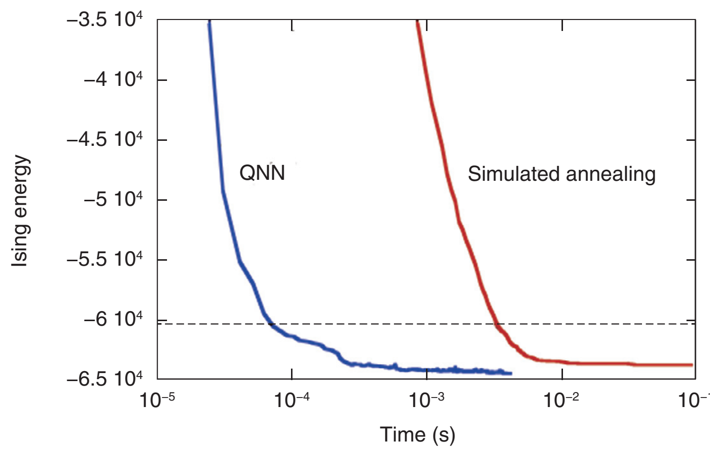


Fig. 3. Solution searching of a 2000-node graph problem with QNN. (a) Graph problem (random graph with 19,990 edges). The pink dots and white lines respectively show the nodes and edges. (b) Solution obtained with the QNN experimentally. The pink dots are divided into red and blue dots; as a result, we can cut the edges shown by the green lines. Larger dots exhibit nodes with a larger number of edges.

$s_i = \Sigma_j J_{ij} c_j$, the feedback signal for the ith DOPO in the next round trip. The feedback signal s_i is used to modulate a light pulse whose frequency is exactly the same as that of the DOPOs, and the pulse is launched to the ith DOPO. As a result, any pair among N DOPOs can be coupled with this scheme. The number of such combinations is $N(N-1)/2$ when the problem is given by a directed graph.

We used the measurement-feedback scheme to construct a QNN with 2048 DOPOs [9], with which we succeeded in finding the solutions to maximum cut problems for a 2000-node graph (**Fig. 3**). In particular,



The blue and red curves show the energies obtained with the QNN and simulated annealing run on a CPU. The dotted line denotes the reference energy obtained with an algorithm called GW-SDP. It took 3.2 ms to reach the reference energy using simulated annealing, while the QNN delivered the solution with the same Ising energy in only 0.7 ms.

GW-SDP: semidefinite programming relaxation algorithm by Goemans and Williamson

Fig. 4. Ising energy as a function of computation time for a maximum cut problem of a 2000-node complete graph (K2000).

when we applied the QNN to a maximum cut problem of a 2000-node complete graph, we obtained a solution that corresponds to a reference Ising energy in less than 100 μs, which is approximately 50 times shorter than the computation time obtained with simulated annealing run on a CPU (central processing unit) (**Fig. 4**).

5. Future prospects

Although QNN research is still in a very early stage, our experimental results suggest that the QNN may outperform conventional digital computers for certain types of problems. We are currently planning to increase the number of DOPOs of our QNN to further widen the performance advantage over digital computers. We also plan to search for applications of QNN by collaborating with researchers from various fields such as statistical physics, mathematics, and computer science.

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Lossless Wavelength Conversion of Single Photons

Nobuyuki Matsuda

Abstract

We demonstrated a new scheme for wavelength conversion of a single-photon wave packet for use in quantum information communication technologies. The scheme enables us to deterministically change the color and shape of a single-photon wave packet in a lossless manner. The scheme is directly applicable to single photons traveling in an optical fiber network and will be a key technology in developing a photonic wavelength interface for quantum networking.

Keywords: quantum communications, single photons, nonlinear optics

1. Introduction

Wavelength (frequency, color) is an important physical parameter of light, and wavelength conversion is essential in current photonics technologies. Applications of wavelength conversion range from simple devices such as laser pointers to the fields of communications, precision measurement, and biomedical sciences.

Wavelength conversion of single photons is crucial for quantum communication, which holds promise for applications such as quantum cryptography and quantum teleportation. For example, the telecommunications wavelength is the wavelength that is suitable for long-distance transmission of photons in optical fiber networks. However, many physical systems such as atoms are sensitive to light with wavelengths in the visible band. In addition, even within the same wavelength band, the wavelengths and spectral shape of photons generally differ from each other depending on the physical properties of the photon sources or on the wavelength channel used for the transmission. Hence, the ability to harness the wavelength of photons, ideally in a lossless manner for scalability, is required in order to distribute quantum information between distant sites via interactions between light and matter or between different light sources.

2. Methods of single-photon wavelength conversion

The wavelength conversion of intense optical pulses induced by themselves (i.e., self-induced) in an optical fiber is shown in **Fig. 1**. The optical pulses, whose initial center wavelength was 1 μm in this example, acquired new wavelength components via nonlinear optical effects (self-phase modulation, four-wave mixing, stimulated Raman scattering, etc.), which can be easily induced by intense optical fields. However, the intensity of a single-photon wave packet is more than 10 orders of magnitude lower than that of ordinary laser pulses.

The first experimental demonstration of wavelength conversion was conducted in 1992. Since then, wavelength conversion of nonclassical light has been widely investigated using nonlinear three- or four-wave mixing (**Fig. 2(a)**), where photon wavelengths can be converted with mediation provided by the energy of other input pump fields [1]. While the intense pump required for a highly efficient conversion tends to simultaneously create noise photons, the demand for scalable quantum networking provides strong motivation for researching the simultaneous realization of lossless and noiseless conversion.

Another nonlinear optical interaction that enables frequency conversion is cross-phase modulation (XPM) (**Fig. 2(b)**), which is a third-order nonlinear

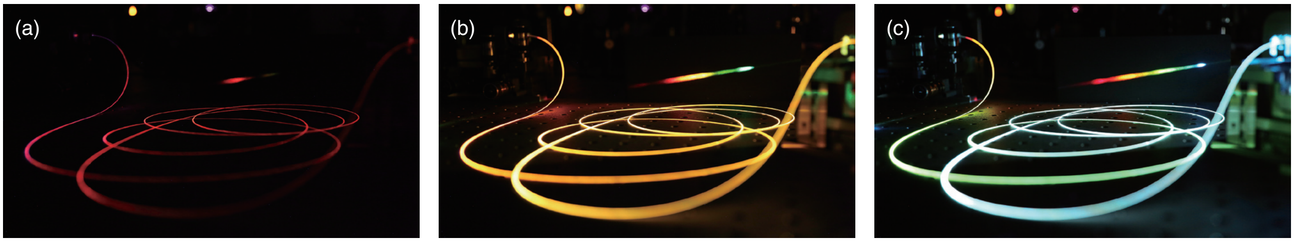

Fig. 1. Self-induced wavelength conversion of intense optical pulses with a center wavelength of 1 μm in an optical fiber. The input power was increased from (a) to (c). The output field was diffracted onto the screen by an external grating (not shown).

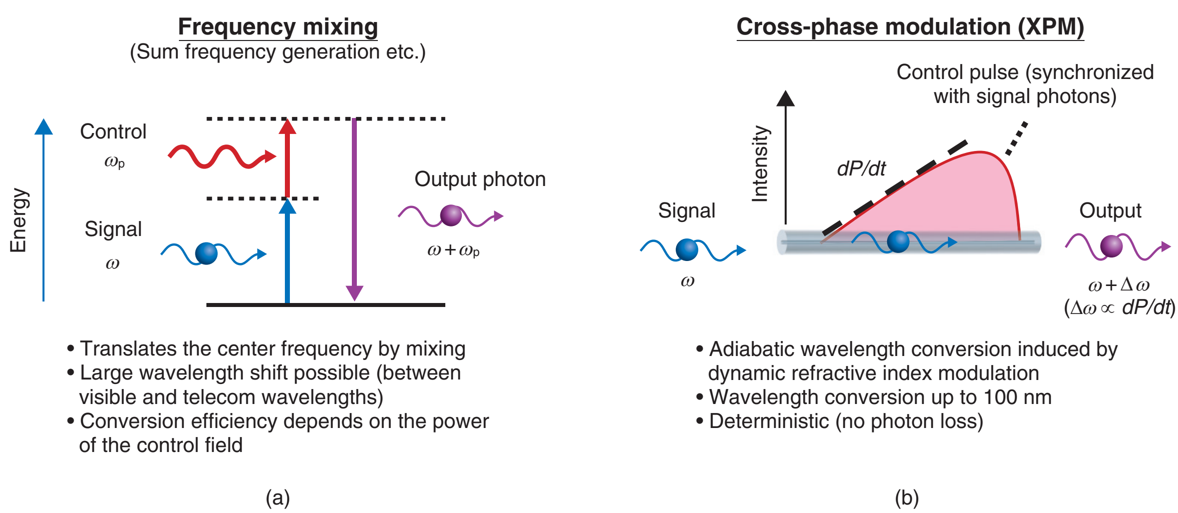

Fig. 2. Nonlinear optical effects for single-photon wavelength conversion.

optical effect that enables the phase of an optical (signal) field to be controlled by another (control) field. XPM provides a function for the wavelength conversion via dynamic phase alteration of an optical field in the following way. The presence of a control pulse with an intensity profile $P(t)$ leads to an intensity-dependent variation in the refractive index variation of the material, which is experienced by the signal field as a phase shift $\phi(t) = 2\gamma P(t)L$, where γ is the nonlinearity strength of a medium and L is the device length. This gives rise to the instantaneous frequency shift

$$\Delta\nu(t) = -\frac{1}{2\pi}\frac{d\phi(t)}{dt} = -\frac{\gamma L}{\pi}\frac{dP(t)}{dt} \qquad (1)$$

of the signal photons. Hence, we can add a wavelength shift, which is proportional to the time derivative of the control field intensity, to the single photons.

Unlike frequency-mixing based schemes, wavelength conversion can be accomplished without any photon loss because the XPM process deterministically occurs regardless of the control field intensity. For example, if we consider standard nonlinear optical fiber (γ = 0.01 /W/mm, L = 10 m) and standard picosecond optical pulses (dP/dt = 600 W/1 ps), we can obtain $\Delta\nu(t)$ = 19 THz, which corresponds to a wavelength shift over 150 nm.

The quantum field to be converted now has a considerably lower intensity than that of the control pulses. Accordingly, a large frequency separation is needed between the two interacting fields in order to eliminate potential noise caused by the nonlinear spectral broadening of the control pulse. Moreover, the two interacting fields must propagate at the same pace; otherwise, $\phi(t)$ will become constant over the

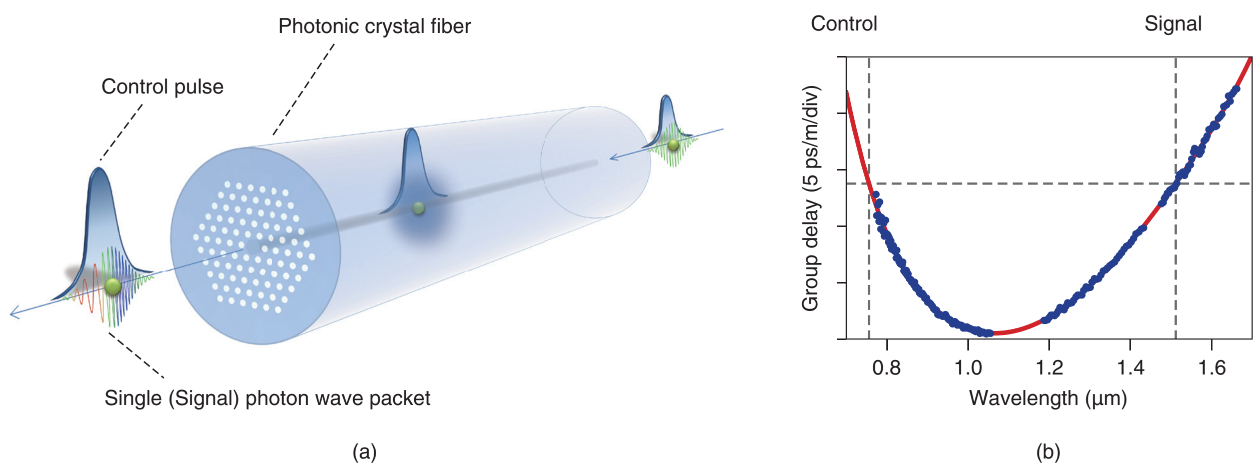

Fig. 3. (a) Schematic of the experimental method. (b) The measured group-delay spectrum of the photonic crystal fiber.

entire wave packet and cancel the frequency shift.

To fulfil the criterion, we used a photonic crystal fiber (PCF) as a Kerr medium with the dispersion property shown in **Fig. 3**. It exhibits two widely separated wavelengths with the same group velocity, thanks to the dispersion property, which is managed by arranging the air-hole claddings that surround the silica core.

3. Experimental results [2]

We converted the wavelength of heralded single photons created via type-II spontaneous parametric down-conversion (SPDC) in a periodically poled potassium titanyl phosphate crystal. The center wavelength of the control field λ_c was chosen to be 756 nm, which satisfies $v_g(\lambda_c) \sim v_g(2\lambda_c)$, where v_g is the group velocity of the PCF (Fig. 3(b)). In this way, both the XPM control pulses and SPDC excitation pulses can be fed from a pulsed laser source. The peak power of the control pulses coupled to the PCF was approximately 350 W.

The dependence on signal delay of the signal photon spectra heralded by the detection of idler photons is shown in **Fig. 4(a)**. The heralded spectrum was markedly modified as the delay time varied. For instance, at the negative delay, where the signal photons are mainly synchronous at the falling edge of the control pulses in the PCF, the spectrum was entirely red shifted because $dP/dt > 0$. In contrast, the spectrum was blue shifted at the positive delay.

Numerical simulation of the frequency modulation was performed based on coupled nonlinear Schrödinger equations including XPM, self-phase modulation, and dispersion. The simulation result (not shown) well described the characteristics of the spectral shifts seen in the experimental data. The maximum wavelength shift was 3.2 nm (0.4 THz), which was limited by the length and the group velocity dispersion (GVD) of the PCF used. Further dispersion engineering of PCFs will be useful for reducing the GVD, which will lead to a larger wavelength shift.

The sum of the photon counts for each delay time is plotted in **Fig. 4(b)**. The total coincidence count remains constant regardless of the delay, demonstrating that the conversion occurred without an observable photon loss. Hence, we have successfully achieved lossless wavelength conversion of single photons.

We applied the scheme to further control the quantum correlation of pairs of photons. The demonstrations included modulation of nonclassical frequency correlation, interference, and entanglement between distant photons [2]. These results demonstrate our scheme's applicability to a wide range of quantum information science and technologies, including computation and metrology.

4. Outlook

We are attempting to further improve the bandwidth and controllability of wavelength conversion. This can be achieved by further engineering the dispersion property of the photonic crystal fiber or engineering the temporal shape of the control pulses. The scheme, achievable in an optical fiber, is compatible

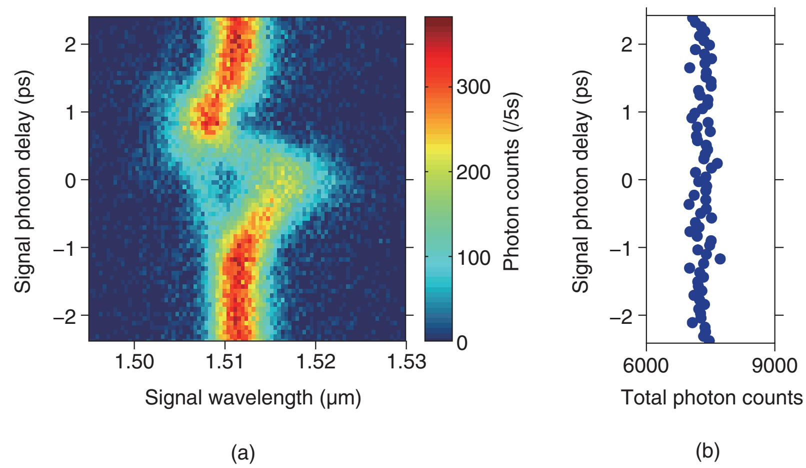

Fig. 4. Experimental results. (a) Delay dependence of the marginal distribution of heralded single (signal) photons. (b) Total photon counts as a function of the delay time.

with the equipment in optical communications networks. With this feature, we aim to develop a photon wavelength interface for flexible quantum networking.

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Demonstration of Realism Violation on a Macroscopic Scale

Kosuke Kakuyanagi, Yuichiro Matsuzaki, Hiraku Toida, Hiroshi Yamaguchi, Shiro Saito, and William John Munro

Abstract

In quantum mechanics, we can realize quantum superposition states, which cannot be understood by the usual *common sense* in our living world. In the microscopic world, such as that experienced by a single electron spin, superposition behavior has been experimentally confirmed. However, it is still controversial as to whether or not we can in principle observe such quantum phenomena in the macroscopic world. At NTT Basic Research Laboratories, we have experimentally tested such macroscopic quantum phenomena by using a macroscopic quantum device.

Keywords: macroscopic realism, quantum mechanics, superconducting flux qubit

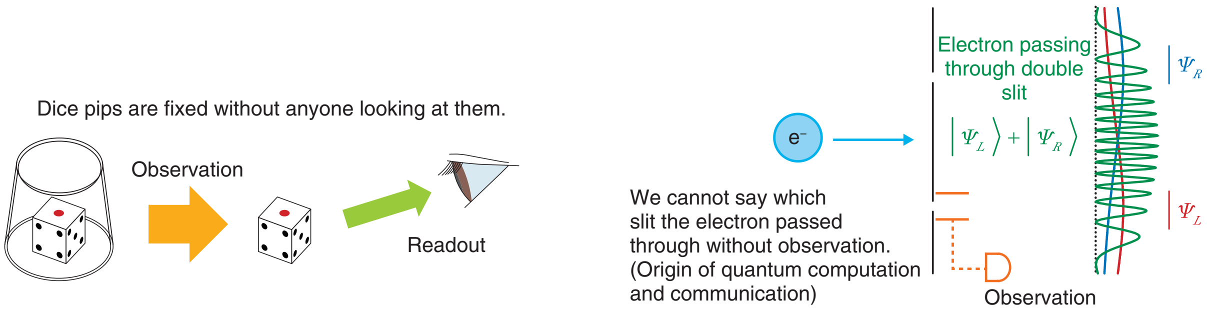
1. Introduction

What is realism? Suppose we have a single die (one of a pair of dice) underneath a cup. If we lift the cup and look at the die, we can see which pips (dots) are on the top surface (1, 2, 6, etc.). We assume that the pips on the die were predetermined before we lifted the cup (**Fig. 1(a)**). The idea of considering objects to be predetermined regardless of our observation of them is called *realism*. In our daily life, we cannot observe any phenomenon that contradicts this realism concept, which seems to support the validity of realism in the macroscopic world.

However, it is known that microscopic particles obey quantum mechanics, and as such, these particles can sometimes display counterintuitive phenomena. As an example, we can conduct an experiment where a single electron passes through a double-slit. If we take just a few measurements of the position of the single electron after passing through the double-slit, the measurements seem to be random. However, if we take many measurements in order to obtain statistical results, the electron position shows an interference fringe, which is typically observed as a wave that passes through both slits. It is worth mentioning that although we cannot divide the single electron into two, this result shows the possibility that the electron spin actually passed through both slits. We can understand this counterintuitive result as a realization of quantum superposition that is described by quantum mechanics. The electron shows a superposition between the state of passing through the right slit and the left slit.

Interestingly, if we observe the path of the electron by placing a detector at one of the slits, the interference fringe disappears. This can be easily understood as the situation in which we can determine the path of the electron by our observation of it, which also indicates that an object state (such as the path of an electron) is not determined until some observations are performed. This kind of phenomenon has been observed in many microscopic systems that obey quantum mechanics (**Fig. 1(b)**).

Because macroscopic objects are composed of microscopic systems such as atoms and electrons, we may think that macroscopic objects should also obey quantum mechanics (why would they not do this?). However, as the example of the die illustrates, realism seems to be valid in the macroscopic world from our experience. Whether the application of quantum



(a) Macroscopic realism

(b) Breaking of microscopic realism (quantum behavior)

Fig. 1. (a) Realism in macroscopic world and (b) realism breaking in microscopic world.

mechanics has a limitation based on size or not has been an unsolved problem ever since the discovery of quantum mechanics. NTT has now demonstrated the violation of realism caused by quantum mechanics in the macroscopic world.

2. Testing the violation of realism

In the macroscopic world, it is thought that the state of objects is not disturbed if we implement optimal observations. For example, we can easily observe the pips on a die without disturbing the die. If we observe objects at different times, we can calculate temporal correlations between the observation results. It is known that if the observation does not induce a disturbance and realism is true, then the temporal correlation obtained by the experimental results should satisfy a specific condition called the Leggett-Garg inequality. This means that if the temporal correlation obtained by experimental observation without disturbance shows a violation of the Leggett-Garg inequality, this result indicates that realism is no longer valid. At NTT Basic Research Laboratories, we found an experimentally more feasible condition that is mathematically equivalent to the Leggett-Garg inequality, so we conducted tests to determine whether our condition was violated as a macroscopic realism challenge.

3. Superconducting flux qubit

We tested macroscopic realism using a superconducting flux qubit, which has been used in many investigations of quantum mechanics. The flux qubit is composed of a number of Josephson junctions. A Josephson junction can be regarded as an inductance similar to an induction coil. This inductance is dependent on the current, so Josephson junctions are a nonlinear inductance. If we fabricate a loop structure with these Josephson junctions, the circuit can form an effective two-level system (qubit) by applying optimal bias magnetic fields. The state of this artificial qubit is then composed of clockwise and anticlockwise currents. Interestingly, the current of this state is around 100 nA, which corresponds to a current of 10^{12} electrons per second. This is an ideal device for checking whether or not quantum superposition can exist at the macroscopic level.

4. Quantum state observation

It is worth mentioning that even if the realism is true, a disturbance induced by the observation could provide us with a violation of the Leggett-Garg inequality. For example, if a die is underneath a cup and we lift up the cup, the cup itself may touch the die. Consequently, the position of the die (and thus, the pips that are apparent) could be changed by this observation, which also demonstrates a violation of the Leggett-Garg inequality. Therefore, to test macroscopic realism, it is crucial to carry out observations with as little disturbance as possible.

We used a superconducting quantum interference device (SQUID) embedded in a microwave resonator to observe the flux qubit with minimal disturbance. The states of the superconducting flux qubits can be distinguished by the magnetic fields from the device because the currents in the two states flow in opposite directions. The SQUID is magnetically coupled with the flux qubit, and the state of the flux qubit changes the inductance of the SQUID. The change in the inductance can be detected by the transmitted

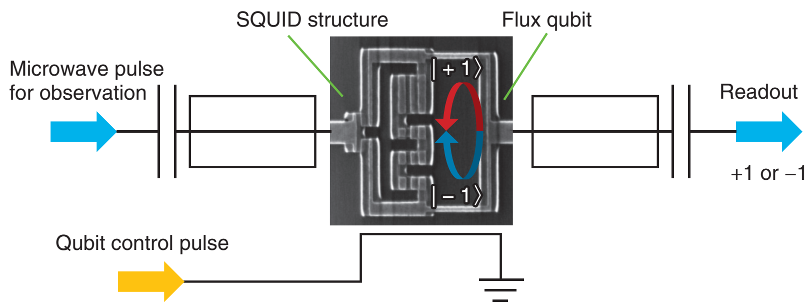


Fig. 2. Readout and control of superconducting flux qubit.

microwave of the resonator. Since this readout does not change the Josephson junctions into voltage states, we can implement a quantum non-demolition measurement[*1] that is known to have a small disturbance on the system (**Fig. 2**).

5. Experimental method

If the superconducting flux qubit obeys quantum mechanics, we should be able to generate a superposition state with a specific gate operation, which we call a quantum state operation. Microwave pulses are used to perform the quantum state operations in our experiments. We set the microwave frequency to be the same as the resonance frequency of the flux qubit, enabling us to control the flux qubit state by changing the amplitude or length of the pulse. We define $|-1\rangle$ and $|+1\rangle$[*2] as the states for the flux qubit. A long period of thermal relaxation initializes the flux qubit state into the $|-1\rangle$ state. When our quantum state operations are performed, our state will evolve as $|-1\rangle \xrightarrow{\text{operation}} |-1\rangle + |+1\rangle \xrightarrow{\text{operation}} |+1\rangle \xrightarrow{\text{operation}} |-1\rangle - |+1\rangle \xrightarrow{\text{operation}} |-1\rangle$ as shown in **Fig. 3(a)**. When the quantum state operations are applied four times, the state returns to the initial state, which is similar to a rotation with a 2π angle. We call this operation a $\pi/2$ pulse. Next, $|-1\rangle + |+1\rangle$ represents a specific quantum superposition state. The objective of our experiment is to check if such a superposition actually exists where the state is not determined until carrying out our observation.

If our qubit obeys quantum mechanics, we should be able to realize the superposition state of $|-1\rangle + |+1\rangle$ by applying the $\pi/2$ quantum pulse to the $|-1\rangle$ state. Without any observation, we can keep the superposition state; thus, an additional quantum operation induces a state of $|+1\rangle$. The measurement result on this $|+1\rangle$ state is always +1. In contrast, if we observe the $|-1\rangle + |+1\rangle$ state, the observation stochastically projects our state into a $|-1\rangle$ or $|+1\rangle$ state. In this case, an additional quantum operation after the observation provides us with the states of $|-1\rangle + |+1\rangle$ or $|-1\rangle - |+1\rangle$, where the expectation value of the measurement result is 0.

We can also consider a case when the realism is correct and perform two experiments (**Fig. 3(b)**). One of them contains two $\pi/2$ operations; we observe the system between these operations. The other experiment is composed of two $\pi/2$ operations without an observation between them. Since we can observe without any disturbance (or only a negligible disturbance), any observation between the operations should not change the state of the objective. Therefore, the measurement results for these two experiments should be the same.

For the reasons explained above, we should observe a difference between these two experiments if our superconducting flux qubit obeys quantum mechanics, while there should be no difference if the realism is correct. We refer to this as our *main* experiment. However, since any observation must have a finite disturbance, we need to quantify the disturbance in the other experiment, which we call the *control* experiment. This can be done as follows. We prepare the state $|-1\rangle$ or $|+1\rangle$, observe the state, and read it out. Then we repeat the same experiment without the observation in the middle. By comparing the difference in the readout results, we can estimate the degree of disturbance that occurs with our observation.

*1 Quantum non-demolition measurement: A measurement in which the state does not change if we prepare an eigenstate.

*2 $|-1\rangle$, $|+1\rangle$: A description method to represent a quantum state. $|-1\rangle$ and $|+1\rangle$ correspond to clockwise and anticlockwise current states. To represent a superposition state, we use for example, $|-1\rangle + |+1\rangle$.

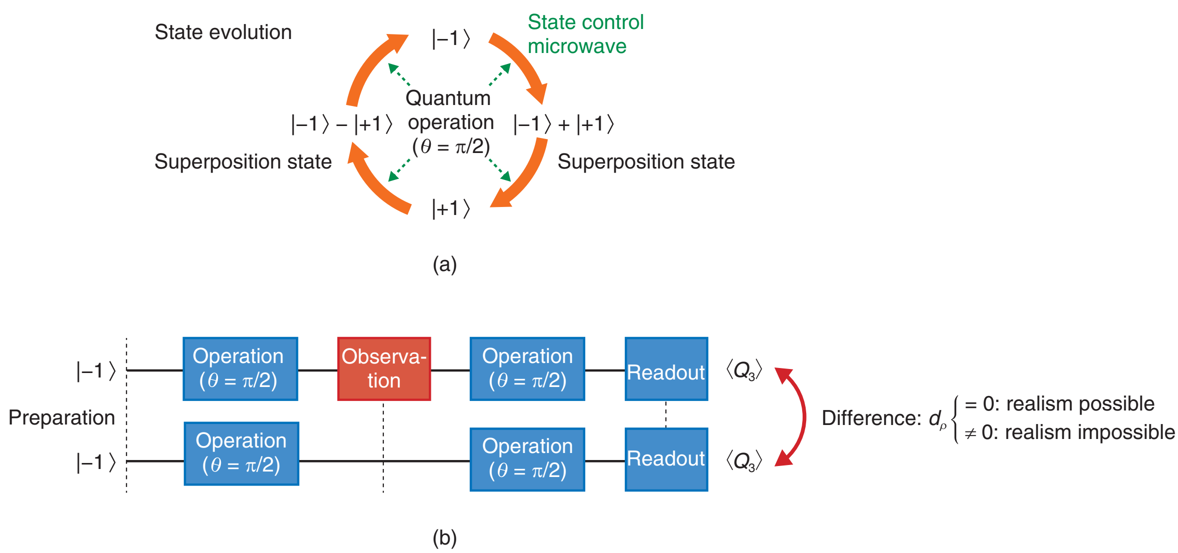


Fig. 3. (a) Quantum state operation and (b) sequence of experiment.

We can now examine how the observation between the quantum operations affects our readout results. For an initial state of $|-1\rangle$ ($|+1\rangle$), we define the difference in the readout between two experiments as d_g (d_e) in the control experiment and d_ρ for our main experiment. If realism is true, d_ρ should be between d_g and d_e, because the state is predetermined before the observation. On the other hand, if d_ρ is outside the region between d_g and d_e, we can conclude that the realism is not valid in this system.

6. Experiment

In our experiment, the energy difference between the two states of the superconducting flux qubit is several gigahertz. To avoid an unwanted thermal effect, we need to reduce our fridge temperature until the thermal energy was much lower than the qubit energy. For this purpose, we used a specific apparatus called a dilution refrigerator that realizes a temperature around 10 mK in our experiment.

By performing our experiment using a superconducting flux qubit, we obtained the values of d_ρ, d_g, and d_e as displayed in **Fig. 4(a)**. Interestingly, d_ρ appears beyond the region between d_g and d_e. This clearly shows that the dynamics of the superconducting flux qubit cannot be explained by the realism despite the macroscopicity of the flux qubit (**Fig. 4(b)**). Furthermore, our experimental results demonstrated the breaking of realism in the superconducting flux qubit current states by 84 times the standard deviation [1].

7. Future plans

We demonstrated that quantum mechanics can be applied on a macroscopic scale with a large supercurrent, where the device itself can be observed with an optical microscope. Our results are crucial in understanding the basics of quantum mechanics. In the future, we aim to conduct measurements with much less observation disturbance and to increase the macroscopic nature of the system by using a larger supercurrent qubit or an ensemble of superconducting flux qubits in order to understand quantum mechanics on a more macroscopic scale.

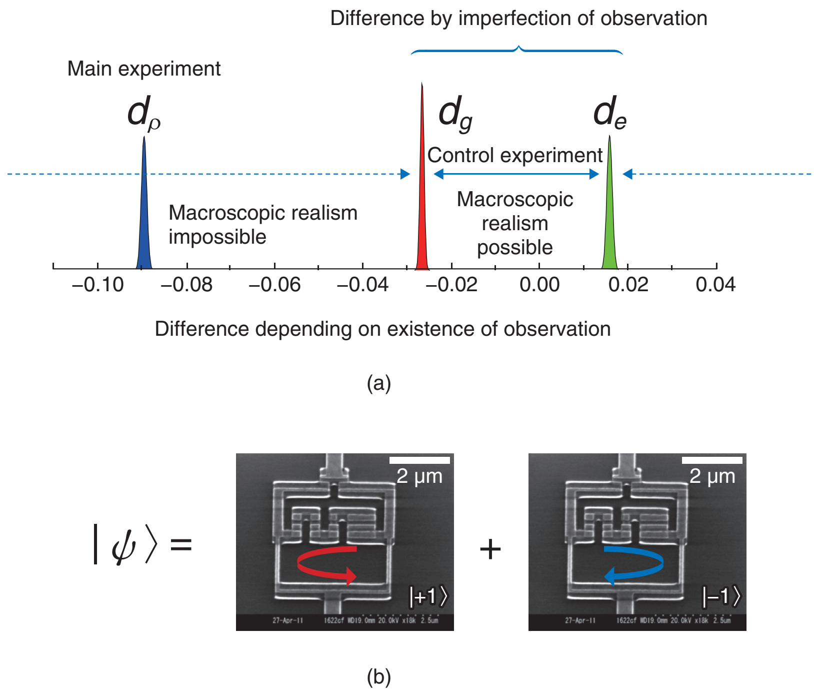


Fig. 4.   (a) Experimental result and (b) quantum superposition of current state.

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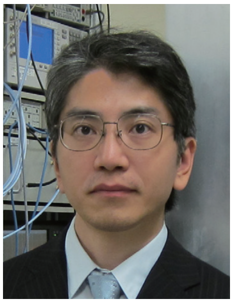

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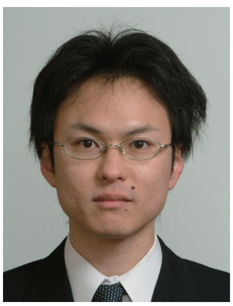

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Coherent Coupling between 4300 Superconducting Flux Qubits and a Microwave Resonator

Yuichiro Matsuzaki, Kosuke Kakuyanagi, Hiraku Toida, Hiroshi Yamaguchi, William John Munro, and Shiro Saito

Abstract

A superconducting flux qubit can be used as a magnetic field sensor, and this has potential applications in many fields such as medical science and biology. If we could realize an entanglement between the superconducting flux qubits, it is expected that such a device would show much better sensitivity than any existing magnetic field sensors. We introduce here our recent research along this direction.

Keywords: superconducting qubit, quantum computation, quantum sensing

1. Introduction

Sensitive magnetic field sensing has many potential applications in medical science and biology. Magnetic resonance imaging (MRI) is a standard technique to obtain three-dimensional (3D) images of materials by detecting their magnetic field information. Magnetoencephalography provides a way to measure the electrical activity of the brain, and this has an important role in medical science. If we can improve the sensitivity of magnetic field sensors, we could characterize materials from high-resolution 3D imaging, or we could target the location of tumors before surgery by detecting small signals.

There are many potential candidates to achieve a sensitive magnetic field sensor. One promising example is the quantum bit (qubit[*1]), which has been the subject of much theoretical and experimental research. The technology for fabricating qubits has mainly been developed for the purpose of implementing quantum computation. However, some types of qubits can be strongly coupled with external fields such as magnetic fields and electrical fields, so it is also possible to use qubits for sensing technology.

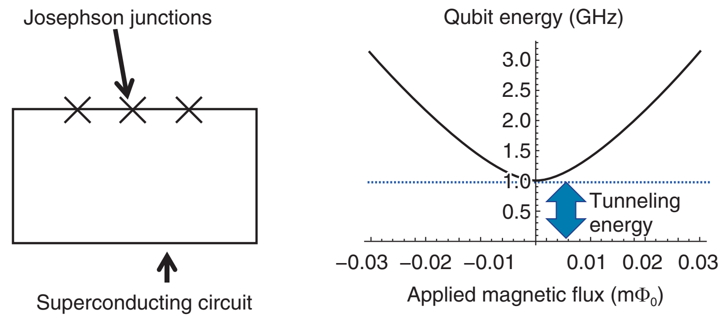
2. Superconducting flux qubit

Among the many possible candidates for qubit-based field sensing, we have investigated a superconducting flux qubit for quantum metrology. A superconducting qubit is an artificial atom, so we can easily design and characterize the device with the desired parameters (a significant advantage to achieve scalability [1]).

The flux qubit is composed of a loop structure containing three Josephson junctions[*2] (**Fig. 1(a)**). With the application of magnetic flux $(n+0.5)\varphi_0$, where φ_0 denotes the quantized magnetic flux and n an integer number, this device acts as a qubit. The resonant frequency of this qubit can be tuned by applying magnetic flux, so a change in magnetic fields can be detected by measuring the resonant frequency. A

*1 Qubit: In classical computation, a bit to store information can represent either 0 or 1. However, a quantum bit (qubit) obeys quantum mechanics, so the state of a qubit can contain a superposition of 0 and 1.

*2 Josephson junction: A structure composed of two superconductors coupled by a thin insulator. This induces a supercurrent that flows without applied voltage due to a tunneling effect.



(a) Josephson junctions (b) Qubit energy

Fig. 1. Superconducting flux qubit.

superconducting flux qubit has two states corresponding to clockwise and anticlockwise persistent current states. When we apply φ_0 magnetic flux, the transition energy from the ground state to the excited states reaches a minimum (**Fig. 1(b)**). The difference between the ground and excited state is called the tunneling energy.

It is also possible to improve the sensitivity if we increase the number of superconducting flux qubits. In particular, if we create an entanglement[*3] that does not exist in the classical world, we can achieve a sensor that has in principle much better performance than any existing devices. For example, superconducting quantum interference devices (SQUIDs)[*4] are used in the medical sciences, but the sensitivity of an entanglement sensor composed of millions of superconducting flux qubits would be a few orders of magnitude higher than that of a SQUID [2].

3. Coupling of microwave resonator and superconducting flux qubits

A microwave resonator is a natural way to achieve large-scale entanglement between multiple superconducting qubits [3]. When an LC (L = inductor, C = capacitor) circuit is fabricated using superconducting materials, the energy levels become quantized, so we can control a few microwave photons inside the resonator. By initiating an interaction between the microwave resonator and the superconducting qubits, we can generate an entanglement between the superconducting qubits, where the microwave photons mediate the interaction between them (**Fig. 2(a)**) [4]. Thus, it is important to achieve strong coupling between the superconducting flux qubit and the microwave resonator.

One way to increase the coupling strength between the superconducting qubits and the microwave resonator is to use collective quantum effects[*5]. By fabricating multiple superconducting flux qubits near the microwave resonator, the superconducting flux qubits show wave-like properties. The collective effect is one such property. This means that by coupling L superconducting qubits with the microwave resonator, the coupling strength is enhanced by a factor of $L^{0.5}$. In fact, 20 superconducting flux qubits were fabricated near a microwave resonator [5], and a frequency shift to indicate such a collective effect was observed in spectroscopic data (**Fig. 2(b)**). However, to achieve a practical quantum device, we need to increase the number of superconducting flux qubits collectively coupled with the resonator, which is important to create a large entanglement between the superconducting flux qubits.

We fabricated a device consisting of 4300 superconducting flux qubits embedded in a microwave resonator (**Fig. 3**) [6]. By spectroscopically analyzing this device, we observed the enhancement of the coupling strength due to the collective effect between the superconducting flux qubits and the microwave resonator. This represents the largest number of coupled

*3 Entanglement: In quantum mechanics, it is possible to create an entanglement that is a stronger correlation than any classical correlation. Entanglement has been shown to play an important role when a quantum computer solves a difficult problem much faster than classical computers.

*4 Superconducting quantum interference device (SQUID): A device composed of a superconducting loop that contains Josephson junctions. This can be used as a magnetic field sensor.

*5 Collective quantum effect: When quantum bits are coupled with a photon or a microwave photon, the ensemble of the qubits behaves like a wave. This phenomenon is called the collective effect.

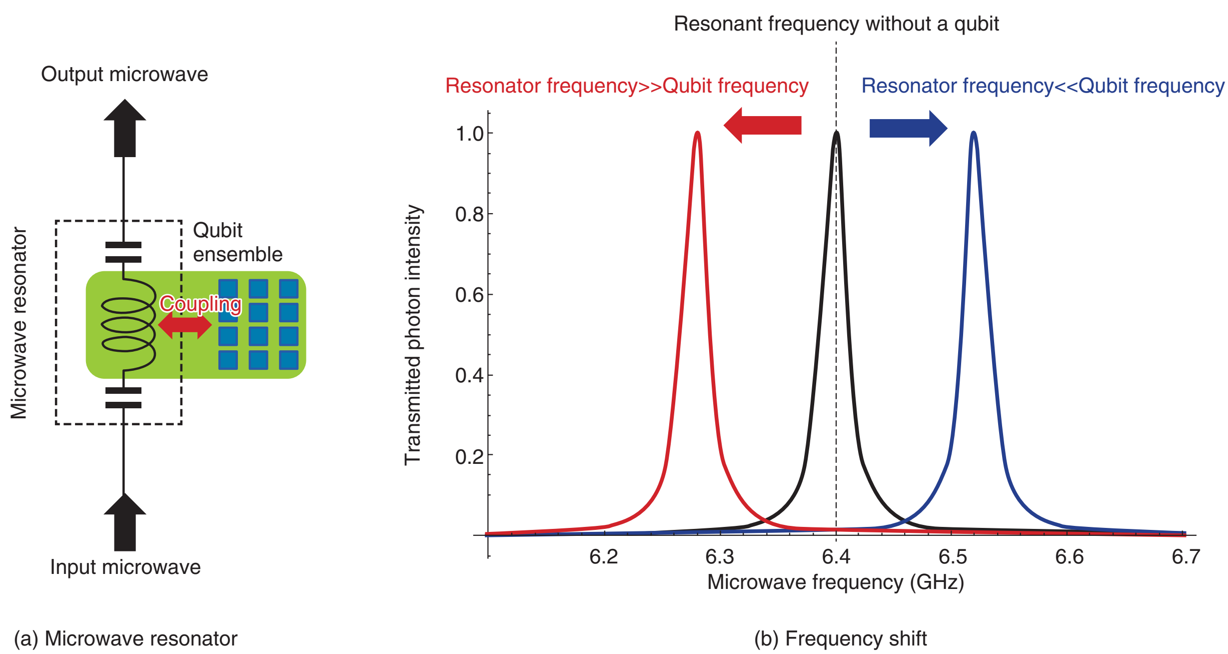


Fig. 2. Coupling of microwave resonator and superconducting flux qubits.

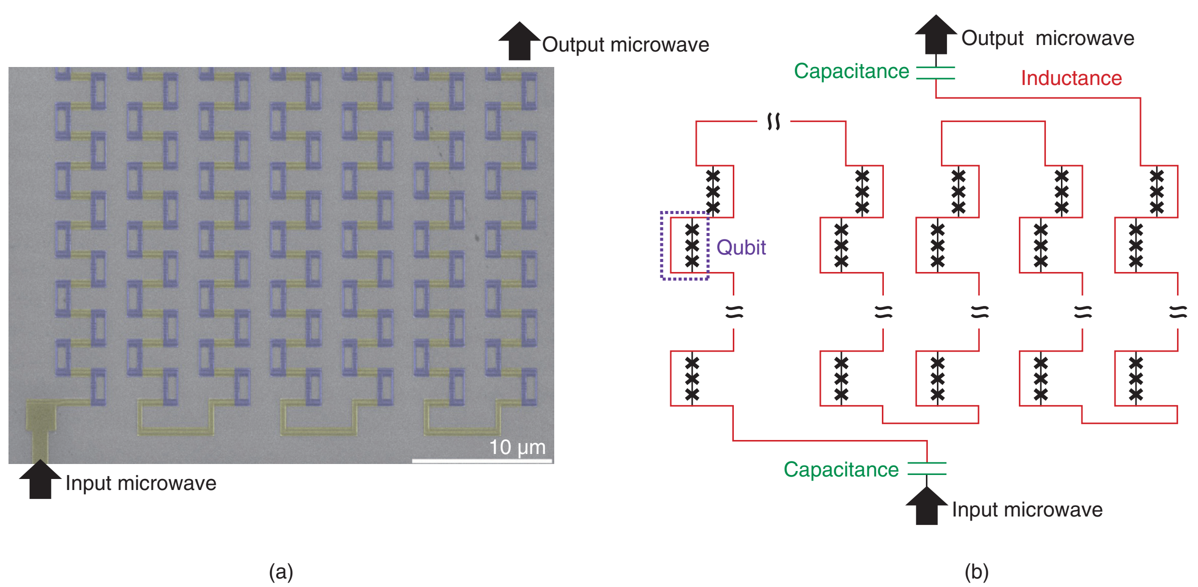


Fig. 3. Schematic of our device.

superconducting qubits realized so far and is a crucial step to realize a large entanglement between superconducting qubits.

4. Spectroscopic measurements of the microwave resonator transmission properties

We placed our sample (sample A) in a dilution refrigerator operating at 20 mK and conducted spectroscopic measurements of the microwave resonator's

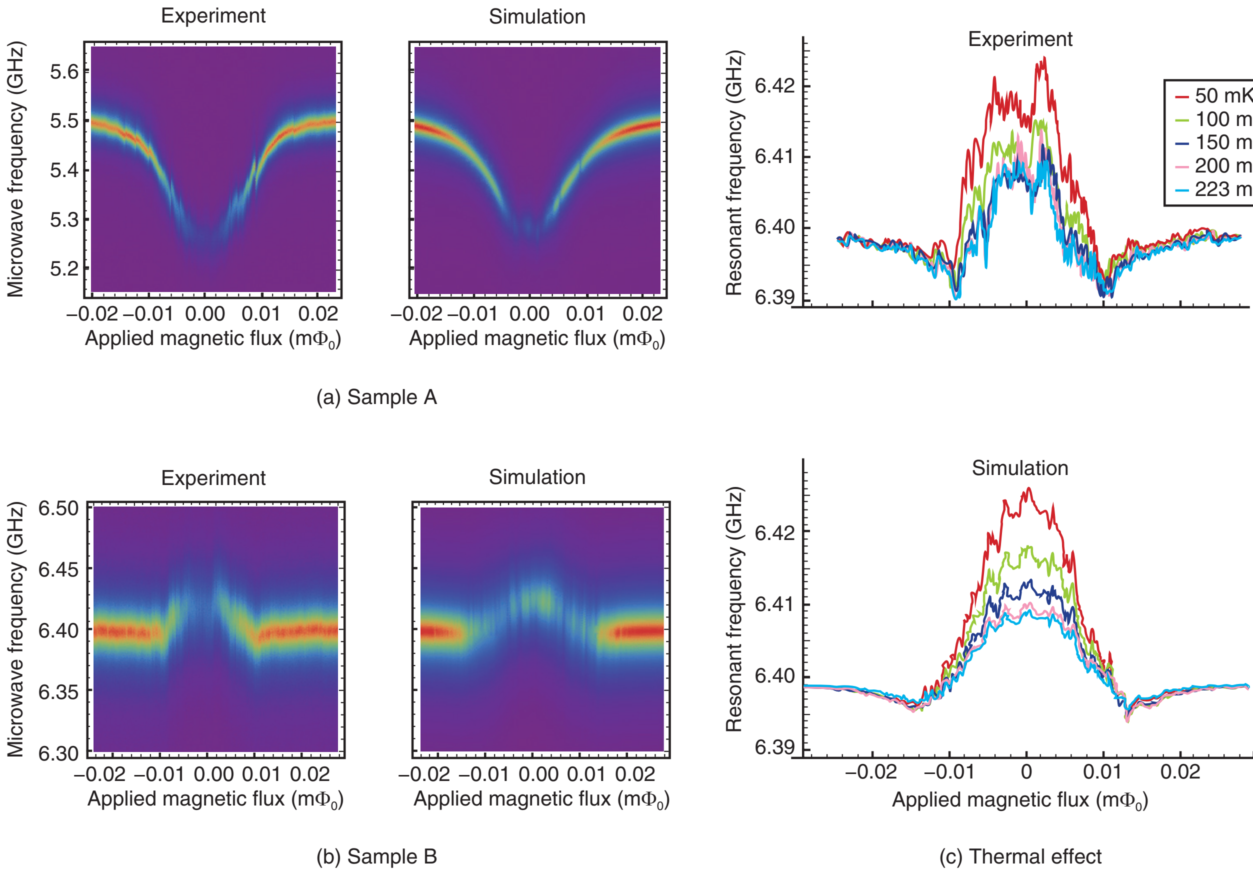


Fig. 4. Spectroscopic measurements of the microwave resonator's transmission properties.

transmission properties. By changing the applied magnetic fields so they were perpendicular to the flux qubits, we observed a frequency shift of approximately 250 MHz (**Fig. 4(a)**). Such a frequency shift is observed due to the collective coupling between the superconducting qubits and the microwave resonator when the resonant frequencies between them are detuned (Fig. 2(b)). We succeeded in reproducing these experimental results using a simple theoretical model that includes collective coupling. We can infer from our numerical simulations that thousands of flux qubits were collectively coupled with the microwave resonator in our experiment.

Next, by using the second sample (sample B) fabricated using different qubit conditions, we observed both positive and negative frequency shifts of tens of megahertz. These frequency shifts are known to occur when the tunneling energy of the superconducting flux qubit is smaller than the energy of the microwave resonator (Fig. 2(b)). The observed frequency shift of sample B is one order of magnitude smaller than that of sample A (**Fig. 4(b)**). This is due to the fact that the tunneling energy of sample B is comparable to the thermal energy of the environment, and the thermal effect suppresses the collective enhancement of the coupling strength. By including the effect of the temperature, we succeeded in reproducing our experimental results with numerical simulations. We measured the temperature dependence of the resonator frequency (**Fig. 4(c)**) and confirmed that an increase in the temperature suppressed the frequency shift of the resonator. Our results confirm that we can control the strength of the collective coupling by changing the temperature.

5. Conclusion

We fabricated 4300 superconducting flux qubits embedded in a microwave resonator and achieved coherent coupling between them. We observed a large frequency shift of the resonator, indicating collective quantum behavior of the superconducting qubits. It is worth mentioning that we could not observe vacuum Rabi splitting*6 that is an indication of strong coupling between the two systems. With the existing technology, we cannot fabricate homogeneous superconducting flux qubits, so the inhomogeneous resonant frequency of the qubits makes it difficult to observe the vacuum Rabi splitting.

To address this problem, it is not possible to create a large entanglement between the qubits for the quantum enhanced magnetic field sensor in the current device. One way to overcome the problem of the inhomogeneous broadening is to fabricate control lines to apply magnetic flux on the qubits, which would enable us to tune the resonant frequency of each qubit. Therefore, as a next step, we aim to achieve strong coupling between the superconducting flux qubits and a microwave resonator by tuning the frequency of the qubits. We will also attempt to generate a large entanglement between the qubits via the microwave resonator, which is useful for constructing an ultrasensitive magnetic field sensor.

*6 Vacuum Rabi splitting: When the resonant frequency of a microwave resonator is the same as that of a qubit, an observed spectroscopic peak can be split into two, which indicates strong coupling between the two systems. This phenomenon is called vacuum Rabi splitting.

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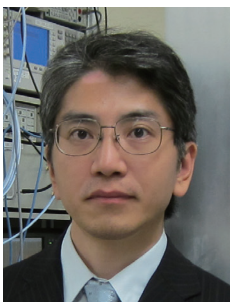

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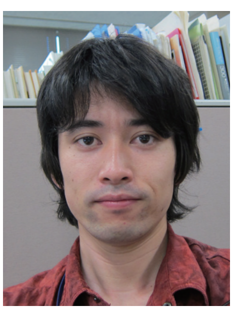

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Creating New Two-dimensional Topological Insulators for Fault-tolerant Quantum Computing

Takafumi Akiho

Abstract

Two-dimensional topological insulators (2DTIs) pave the way to explore novel quasiparticles for fault-tolerant quantum computing and to create devices utilizing spin degree of freedom. However, host materials that realize 2DTIs have so far been limited to two systems. In this article, we propose a strained quantum well structure as a new 2DTI candidate and demonstrate that strain enhances the energy gap and leads to superior bulk insulation properties.

Keywords: two-dimensional topological insulators, fault-tolerant quantum computing, strain band engineering

1. Introduction

Topological insulators (TIs) featuring insulating bulk and conducting edge states originating from topologically nontrivial inverted band structures have been attracting much interest. Topology is a field of mathematics; objects with shapes that can be made to conform to each other by a continuous deformation are said to have the same topology. TIs are insulators but have a different topology than normal insulators (NIs), as their band structures cannot be transformed continuously into each other [1]. Therefore, at the interface between a TI and NI (which includes a vacuum), the band gaps must close, which results in conducting edge states at the interface (**Fig. 1**). The Nobel Prize in Physics 2016 was awarded to US scientists for "Theoretical discoveries of topological phase transitions and topological phases of matter." This further fueled research interest in topological materials science.

TIs were first proposed for two-dimensional (2D) systems. The theory predicted ballistic and quantized transport at the edge of TIs. Moreover, helical spin current in which the spin direction is locked to the direction of momentum (e.g., up spins to the left and down spins to the right) was predicted. The helical spin current can be used as a spin source with semiconductors to create novel spintronic devices.

Additionally, it is theoretically predicted that Majorana fermions show up in topological superconductors where the edge states of a TI are proximitized by a superconductor. Majorana fermions have a different nature than conventional particles of fermions and bosons, and they are promising for use in fault-tolerant quantum computing because they are protected from most types of decoherence. Thus, TIs have been proposed as a platform for exploring spintronic applications and exotic quasiparticles.

In this article, we introduce a strained quantum well (QW) structure as a new 2DTI candidate and demonstrate that strain enhances the energy gap and leads to superior bulk insulation properties [2].

2. New 2DTI candidate

Although various materials have been theoretically proposed as 2DTI candidates, experimental reports of transport properties clearly indicative of 2DTIs have so far been limited to two systems, cadmium telluride/mercury telluride (CdTe/HgTe) QWs and indium arsenide/gallium antimonide (InAs/GaSb) QWs, both of which are lattice-matched semiconductor

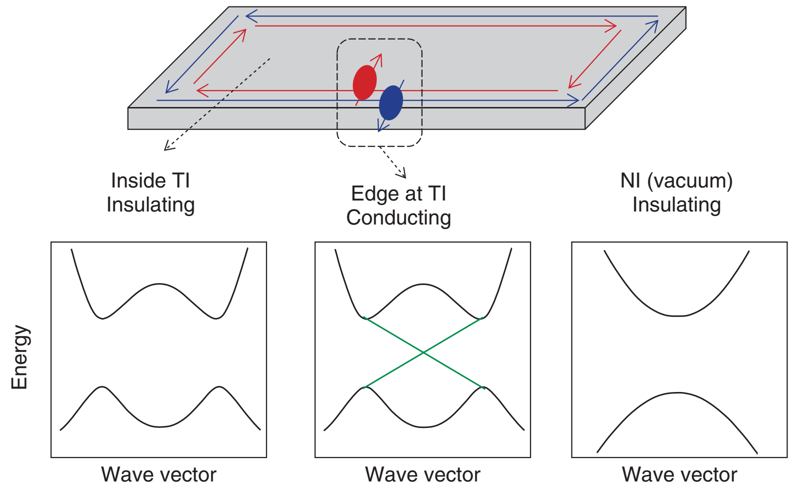


Fig. 1. Schematic energy dispersion of a topological insulator. TIs have different topology than normal insulators (including vacuum). Therefore, the band gaps must close at the interface between a TI and NI, resulting in conducting edge states.

heterostructures. Historically, the CdTe/HgTe system was first predicted to be a 2DTI, which was subsequently followed by the InAs/GaSb system.

InAs and GaSb are conventional semiconductor materials that are easier to work with than HgTe. The InAs/GaSb system has a key advantage of being *in situ* tunable between normal and topological insulating phases. However, the residual bulk conductivity in the topological insulating phase has been an obstacle to investigating edge transport. In this article, we propose InAs/indium gallium antimonide (InGaSb) strained QWs as a new 2DTI candidate that can overcome this problem.

3. Strain band engineering

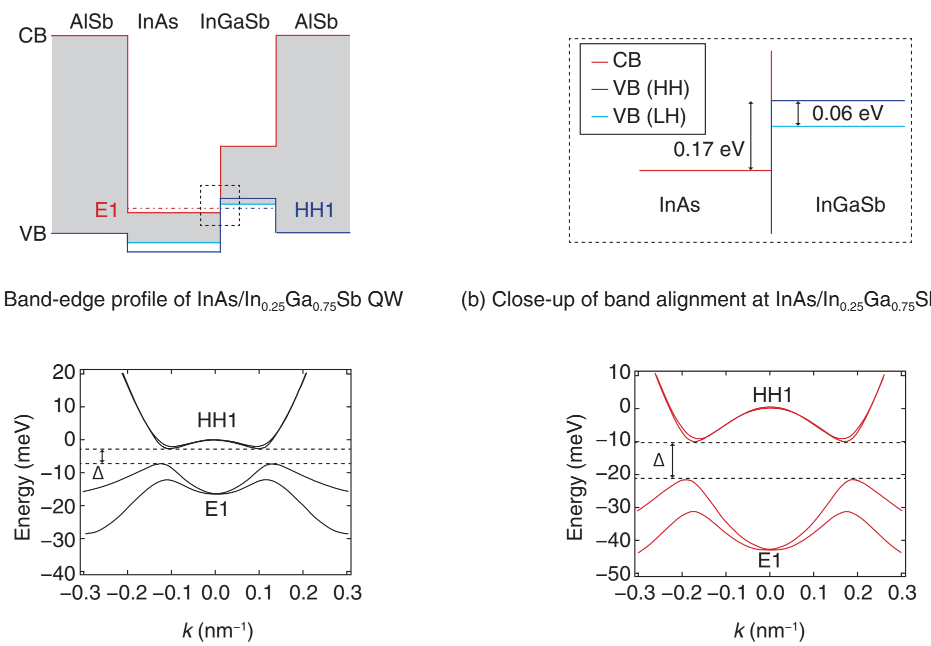
The band-edge profile of an InAs/$In_{0.25}Ga_{0.75}Sb$ strained QW is shown in **Fig. 2(a)**. Electrons and holes are separately confined to the InAs and $In_{0.25}Ga_{0.75}Sb$ QWs, where they form subbands E1 and HH1, respectively. The conduction band (CB) bottom of InAs is located ~0.17 eV below the valence band (VB) top of $In_{0.25}Ga_{0.75}Sb$ (**Fig. 2(b)**). Note that this ordering of the band extrema is opposite to that in ordinary semiconductors. This band inversion is a prerequisite for topological insulators.

Additionally, $In_{0.25}Ga_{0.75}Sb$ has a larger lattice constant than aluminium antimonide (AlSb), which induces compressive strain in the $In_{0.25}Ga_{0.75}Sb$ layer. This splits the VB edge of the heavy hole (HH) and light hole (LH) by 0.06 eV (Fig. 2(b)), strengthening (weakening) the interaction between CB and HH (LH). From these relations, we expect larger band inversion for strained InAs/InGaSb QWs than unstrained InAs/GaSb QWs.

We calculated the energy dispersion relation by using the **k·p** method because the energy gap Δ originating from the interaction between E1 and HH1 opens at a finite wave vector **k**. The band structure of an unstrained InAs/GaSb QW is shown in **Fig. 2(c)** in comparison to that of a strained InAs/$In_{0.25}Ga_{0.75}Sb$ QW (**Fig. 2(d)**) for InAs and (In)GaSb thicknesses of 10 and 6 nm, respectively. As the calculations show, the InAs/$In_{0.25}Ga_{0.75}Sb$ strained QW has larger band overlap and larger Δ than the unstrained InAs/GaSb QW, suggesting favorable bulk insulation properties in the strained InAs/InGaSb QW.

The heterostructures studied were grown by molecular beam epitaxy on Si (silicon)-doped (001) GaAs substrates (**Fig. 3(a)**). The QWs consist of InAs and 5.9-nm-thick $In_{0.25}Ga_{0.75}Sb$, sandwiched between AlSb barrier layers. Four heterostructures with different InAs layer thickness (8.5, 9.1, 10.0, 10.9 nm) were prepared.

The heterostructures were processed into Hall bar devices (width: 50 µm, voltage-probe distance: 180 µm) by using lithography (**Fig. 3(b)**). We applied current I and obtained longitudinal resistance R_{xx} from voltage V_{xx} and Hall resistance R_{xy} from voltage V_{xy}. Gate voltage V_{FG} was used to vary the carrier density. Magnetic field B was applied perpendicular to the sample plane.



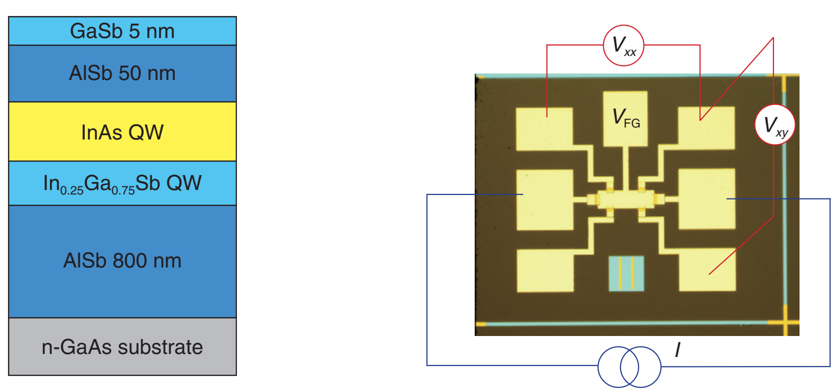
(a) Band-edge profile of InAs/$In_{0.25}Ga_{0.75}Sb$ QW

(b) Close-up of band alignment at InAs/$In_{0.25}Ga_{0.75}Sb$ interface

(c) Energy dispersion of unstrained InAs/GaSb QW

(d) Energy dispersion of strained InAs/$In_{0.25}Ga_{0.75}Sb$ QW

Fig. 2. Band structures of InAs/(In)GaSb QWs.



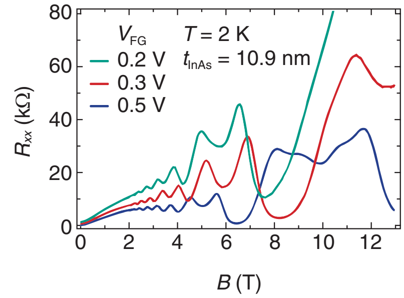
(a) Schematic image of layer structure

(b) Picture of Hall bar device and measurement configuration

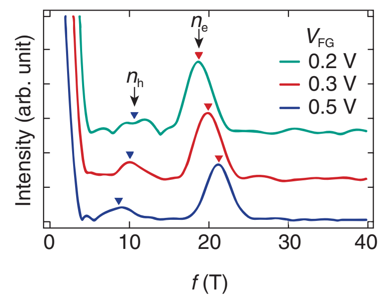
Fig. 3. Sample structure.

4. Quantitative analysis of band inversion

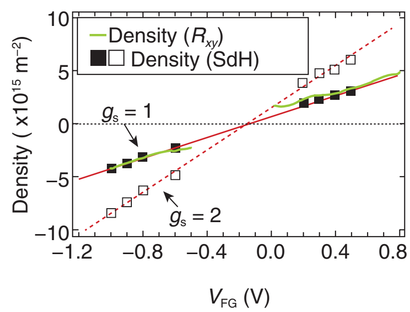
In **Fig. 4(a)**, R_{xx} vs. B is plotted for different V_{FG} values at 2 K. The sample contained a 10.9-nm-thick InAs QW. Due to the quantization of cyclotron motion of electrons and holes by a strong magnetic field, R_{xx} oscillates as a function of B (SdH (Shubnikov-de Haas) oscillation). Fast Fourier transform (FFT) analysis of the SdH oscillations revealed two frequency components f (**Fig. 4(b)**). The one with the corresponding carrier density increasing (decreasing) with V_{FG} can be identified as being associated with electrons in InAs (holes in InGaSb). The coexistence of electrons and holes indicates that the band is inverted and the Fermi level intersects both electron-like and hole-like bands.



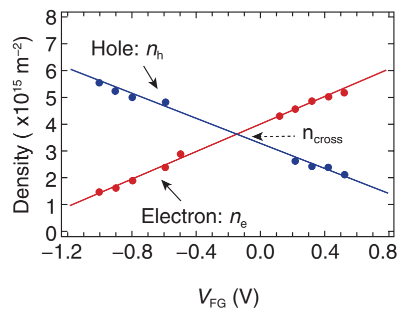
(a) SdH oscillations with different gate voltages V_{FG}



(b) Results of FFT analysis of SdH oscillations



(c) Comparison of carrier densities deduced from Hall resistance R_{xy} and SdH oscillations



(d) Electron density n_e and hole density n_h vs. V_{FG}

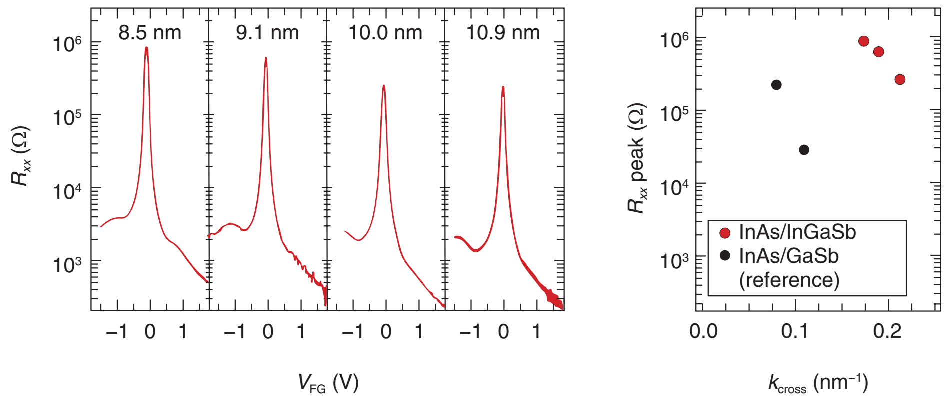
Fig. 4. Quantitative evaluation of band inversion.

Carrier density n is related to f as $n = g_s f(e/h)$. Here, h is Planck's constant, e is elemental charge, and g_s is spin degeneracy. Moreover, g_s can take a value of 1 or 2; $g_s = 1$ (2) means that the energy levels are spin-split (degenerate). To determine whether g_s = 1 or 2, we compared the total carrier densities deduced from R_{xy} with those deduced from SdH oscillations for both spin-degenerate and spin-split cases. Interestingly, we found the energy levels were spin split ($g_s = 1$) in the InAs/InGaSb strained QW (**Fig. 4(c)**). Such characteristics have not been observed in the conventional InAs/GaSb QWs. One possible origin of the spin splitting is spin-orbit interaction; however, further investigation is necessary to clarify the origin.

A quantitative measure of band inversion is given by k_{cross} [$= (4\pi n_{cross}/g_s)^{1/2}$], the wave vector at which the anti-crossing of E1 and HH1 occurs. From the linear fit of the dependence of electron density n_e and hole density n_h on gate voltage (**Fig. 4(d)**), we obtained the density n_{cross} at the charge neutrality point (where $n_e = n_h$) of 3.6×10^{15} m^{-2}. Using the n_{cross} and g_s values, we obtained $k_{cross} = 0.21$ nm^{-1}.

5. Enhanced bulk resistivity

The R_{xx} peak height at the charge neutrality point measured at 0.25 K, which mainly reflects in-gap states in the bulk, increased with decreasing InAs thickness and reached 889 kΩ (corresponding resistivity of ~10 h/e^2) for the 8.5-nm-thick QW (**Fig. 5(a)**). Higher peak resistance indicates superior bulk insulation properties. The obtained R_{xx} peak values are plotted as a function of k_{cross} (**Fig. 5(b)**). The data for InAs/GaSb QWs are also plotted as a reference. The InAs/InGaSb strained QWs exhibited higher bulk resistivity in the deep band inverted regime than that of the reference. Generally, the residual bulk conductivity problem becomes more significant as the band inversion increases. Therefore, it was hard to satisfy high bulk resistivity and deep band inversion at the same time with unstrained InAs/GaSb QWs. The **k·p** calculation predicts that an even larger energy gap can be obtained by exploiting higher strain, that is, a higher In composition in the InGaSb layer. This means that there is much room to improve the bulk insulation properties by optimizing the strained QW



(a) R_{xx} vs. V_{FG} with different InAs thicknesses. Peak height reflects bulk resistance.

(b) R_{xx} vs. k_{cross}

Fig. 5. Demonstration of high bulk resistance in deep band inverted regime.

structure.

6. Conclusion

High bulk resistivity in the deep band inverted regime was obtained by using InAs/InGaSb strained QWs. Our results demonstrate that InAs/InGaSb strained QW structures are a promising platform for robust 2DTIs, where intrinsic edge physics can be studied with the advantage of good bulk insulation deep in the band-inverted regime. As the next step, we plan to demonstrate quantized edge transport by optimizing InAs/InGaSb strained layer structures. The origin of the spin-splitting transport properties should also be clarified. Demonstration of the quantized edge transport in strained QWs will be an important step in studies of superconductor/TI heterojunctions for fault-tolerant quantum computing.

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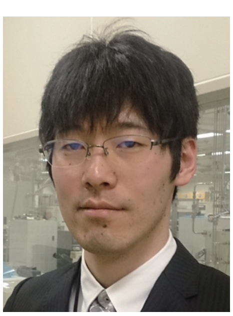

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Implementation Security of Quantum Key Distribution

Kiyoshi Tamaki

Abstract

Quantum key distribution is the ultimate cryptography in that it is theoretically secure against any possible eavesdropping. This ultimate security is an attractive feature, and companies and organizations in several countries, including Japan, are working on the deployment of networks for quantum key distribution. However, further research is needed to achieve the ultimate practical security, rather than security in principle. In this article, we introduce our recent research activities toward achieving the ultimate practical security.

Keywords: quantum key distribution, information-theoretic security, implementation security

1. Introduction

We often rely on data encryption when sending confidential information such as passwords or private information over the Internet. Modern cryptography is commonly used for this, and with such cryptography, we exploit the fact that it is difficult to solve particular mathematical problems such as the factorization of large numbers by means of existing technologies and algorithms. A crucial problem is that there is no guarantee that these problems are indeed hard to solve. This implies that the security of modern cryptography would be threatened by the development of new algorithms and the technologies to run them.

Researchers have recently been working on new forms of cryptography to protect confidential information sent over a communication channel. These use the laws of nature (such as the properties of a photon) and are called quantum cryptography. In this article, we discuss quantum key distribution (QKD), a particular type of quantum cryptography. One of the remarkable features of QKD is that it is secure against any possible eavesdropping. This is because one has to break the laws of nature to crack QKD, which is of course impossible. Therefore, unlike other modern forms of cryptography, QKD is secure against current eavesdropping technologies and will remain secure against all future technologies.

Optical communications technologies can be utilized in QKD since QKD is part of the optical communications family. However, we need to consider how to generate, manipulate, and detect a single photon, which is far beyond the capabilities of the technologies used in standard optical communications. Research and development of technologies for these tasks has resulted in the commercialization of a QKD system [1], and organizations in several countries, including Japan [2], have started field testing it [3] to determine how it can be integrated with current technologies.

2. Security of QKD

An Internet search for "hacking, QKD" will lead to a number of articles about the successful hacking of QKD. These articles contradict what is mentioned in this article, and to determine what is happening, we need to give a more precise argument about the security of QKD. First, a theory called the security proof of QKD guarantees the security of QKD. When we work on a security proof, we use mathematical models for QKD devices, which are constructed by making assumptions on actual devices. We then apply quantum mechanics and information theory based on these models to create a security argument. For instance, we typically assume that a phase modulator can achieve exact phase modulations of 0, $\pi/2$, π, and $3\pi/2$. Quantum key distribution is shown to be secure under such an assumption, but this security statement cannot be applied in practice because the exact modulation cannot be achieved due to noise or imperfections. In other words, the security proof provides us with a conditional statement such as "If a QKD device satisfies these assumptions, then it is secure." A security proof does not tell us anything about what has to be done to satisfy all the assumptions. Therefore, when some assumptions do not hold, the security argument fails, allowing a hacker to crack QKD systems. This is exactly what is happening in the aforementioned articles found on the Internet. In other words, one cannot crack QKD when all the underlying assumptions hold, but one can crack it by exploiting the gap between the assumptions made in theory and the actual properties of QKD devices.

Therefore, to guarantee the implementation security of QKD, that is, the security of QKD when it is implemented, we need to bridge this gap. There are two approaches for this: (1) developing QKD devices that fulfill all the assumptions, and (2) developing a security proof that accommodates the imperfections of actual QKD devices. Researchers are working on both of these. We have mainly taken the latter approach, which is briefly introduced below.

3. Guaranteeing implementation security of QKD

There are three main components in QKD: a sending device, a quantum channel, and a receiving device, all of which need to be properly implemented in a QKD experiment. When we conduct a security analysis of QKD for a quantum channel, we assume a worst-case scenario in which a quantum channel is totally under the control of an eavesdropper. This scenario includes a case in which an eavesdropper sneakily replaces a noisy and lossy quantum channel with one without any noise and loss, and all the eavesdropping attempts are disguised, as they are mistaken for noise and loss. Therefore, although a quantum channel may be useful to increase the communication speed, it does not provide any advantage in terms of security.

To improve security, therefore, we have to seriously investigate the sending and receiving devices. We discuss here the imperfections of a phase modulator as an example of a sending device. As we mentioned above, with some security proofs, exact phase modulation is assumed. Unfortunately, such an assumption is difficult to satisfy in reality. There is a security proof accommodating such imperfections [4]; however, according to this security proof, a slight degradation in the modulation precision severely limits the communication distance, as shown in **Fig. 1**. This figure shows the distance (km) dependency of the communication speed in log scale. As can be seen in this figure, just a slight modulation error, such as those of 3.6 and 7.2 degrees, reduces the communication distance significantly. For instance, an error of 3.6 degree halves the achievable communication distance compared to perfect phase modulation.

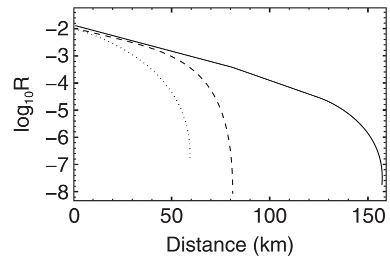

Fig. 1. Distance dependency of communication speed (R) on a log scale. Solid, dashed, and dotted lines respectively represent cases with perfect phase modulation, a 3.6-degree modulation error, and a 7.2-degree modulation error.

To solve this problem, we checked all the steps in a QKD protocol and found that some data, which were believed to be useless and were thus discarded, were actually the key to solving the problem. We previously proposed a data-processing scheme to enable us to make full use of the data and successfully solved this problem [5]. The graph in **Fig. 2** shows the distance (km) dependency of the communication speed based on the same experimental setup as in Fig. 1, but where its data processing was based on our scheme. The three lines are almost superposed, meaning that phase-modulation error was not an issue.

So far, the discussion here has focused only on the effect that manipulation with low precision has on security, where an eavesdropper would exploit deviations of an imperfect photon from the ideal photon. Unfortunately, there is another type of eavesdropping strategy in which an eavesdropper actively tries to obtain information that is processed within a QKD device. In this case, an eavesdropper shines a very bright pulse into a QKD device and learns the internal state of the device by monitoring the back-reflected light.

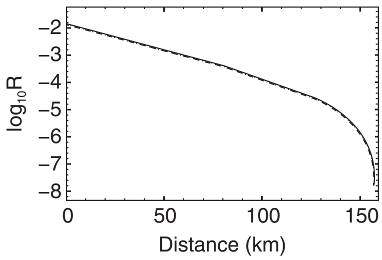

Fig. 2. Distance dependency of R of our scheme on a log scale. Here also, the solid, dashed, and dotted lines respectively represent cases with perfect phase modulation, a 3.6-degree modulation error, and a 7.2-degree modulation error.

This type of eavesdropping seems to be circumvented by preventing illegitimate pulses from entering a QKD device. This may be possible by installing an optical isolator in front of the QKD device. However, no optical isolator can perfectly extinguish the incoming illegitimate pulses, and we have to seriously consider how to accommodate these attacks in a security proof. In our attempts to do so, we noticed that QKD under this type of attack can be seen as QKD with a multi-mode pulse. We therefore generalized this idea to construct a security proof that was valid against any attack for any given mathematical model of a sending device [6]. This security proof is general in the sense that we do not need to redo a security proof every time we find a new attack, and we are hoping that our security proof will play a key role in guaranteeing security when implementing QKD.

4. Future prospects

Although only a sending device was discussed here, we have seen rapid progress on the receiving-device side as well (see [3] for a recent review of QKD). We expect that it will not be long until we establish practical ultimate security of QKD. We will continue to conduct research to make this a reality.

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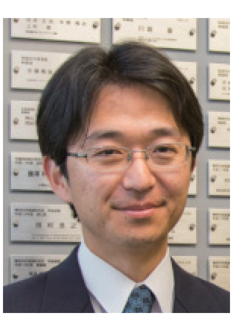

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Heart Rate Measurement with Video Camera Based on Visible Light Communication

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Abstract

We have developed a system based on optical camera communication and an encoding method that can transfer the heart rates (HRs) of multiple people with high precision. The system can potentially measure and transfer the HRs of hundreds of people with their positional information. The unique system is composed of HR sensor units and a conventional camera. It is presented here along with the novel event timing encoding method.

Keywords: visible light communication, heart rate, event timing encoding

1. Introduction

Recent advances in light emitting diodes (LEDs) have opened up numerous possibilities for new visible light communication (VLC) technologies and systems [1]. VLC systems typically use LEDs and photodiodes. However, much progress has also been made recently in image sensor technology. Consequently, optical camera communication (OCC), a VLC system that uses LEDs and image sensors, has been attracting a lot of attention. A typical OCC system is composed of a single camera with multiple sensors distributed in sight of the camera [2]. OCC is advantageous in that it can obtain data from multiple points together with the sensor positions.

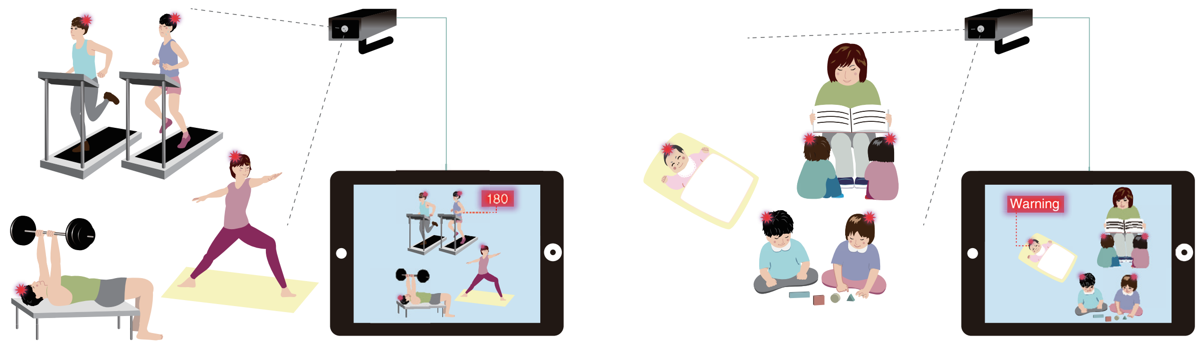
From another point of view, as the population of elderly citizens increases, healthcare monitoring is becoming an important and promising application. For example, suppose a situation where a member of a gym is wearing a heart rate (HR) sensor that transmits his or her heart beat (HB) in real time (**Fig. 1(a)**). The gym staff could provide immediate aid to the member if they observed danger signs in the member's HR [3]. This technology will also be beneficial for small children and infants. One potential application is monitoring the HRs of sleeping infants in child care centers (**Fig. 1(b)**). Monitoring their HRs would enable a caregiver to quickly deal with abrupt HR changes such as those associated with sudden infant death syndrome [4].

However, with the conventional radio frequency wireless network, this task is not as easy as one may think. The network may not work well if there are a large number of devices [5] and positional information is difficult to obtain.

Therefore, we have developed an OCC system [6] and an event timing encoding (ET encoding) technique [7] that can precisely transfer the intervals of HB events with a conventional camera. The high spatial directionality of visible light enables multiple data channels to be transmitted simultaneously through different optical paths along with the positional information of sensors. In addition, OCC can potentially be combined with natural image analysis in the future.

2. Method to transfer precise HB timing

As explained in the introduction, the system is composed of a sensor unit and camera (image sensor). The capturing speed of a commonly used camera is usually limited to 30 or 60 frames per second, which is not high enough to observe the event timing of the HB. Furthermore, the system only detects the 'on/off'



(a) (b)

Fig. 1. (a) In this scenario, a member of a gym is wearing a heart rate (HR) sensor. The gym staff can advise the member by monitoring the HR or provide immediate aid if danger signs are observed. (b) In this scenario, the OCC system is used to support child care center caregivers in monitoring babies who are napping. Information can be easily superimposed on the captured image by using OCC.

state of the LED for simplicity and robust processing. If someone simply flashes the LED at a sensor unit when an HB event occurs, the captured images on the camera side give us only 33 ms of time resolution. However, the requirement is less than 4-ms resolution even for simple HR analysis.

ET encoding is designed to overcome this problem. The idea is that it first signalizes the occurrence of the HB event and then refines the relative timing with consecutive LED patterns. In practice, the unit simulates the frame rate of the camera and switches the LED 'on' and 'off' using this clock (LED clock). When the unit detects an HB event, it marks the timing location of the event within this LED clock frame. The unit first sends an 'on' signal after the detection to inform the decoder of the LED clock frame. When the camera detects this first 'on' signal, we can determine on the camera side that the event occurred somewhere in the previous frame shot. The unit continuously sends details about the location of the event in the LED clock frame. From these data, we can refine the timing of the event. In other words, ET encoding tells the LED clock frame that the event is occurring and sends the natural binary expression of the event timing in the frame. The flow chart for sending the event timing by flashing an LED is shown in **Fig. 2**. The encoding image is shown in **Fig. 3**.

The time resolution of the HB interval in ET encoding is calculated as

$$R_1 = \frac{1}{2^{(T_{\min}F_z - 1)}F_z}, \quad (1)$$

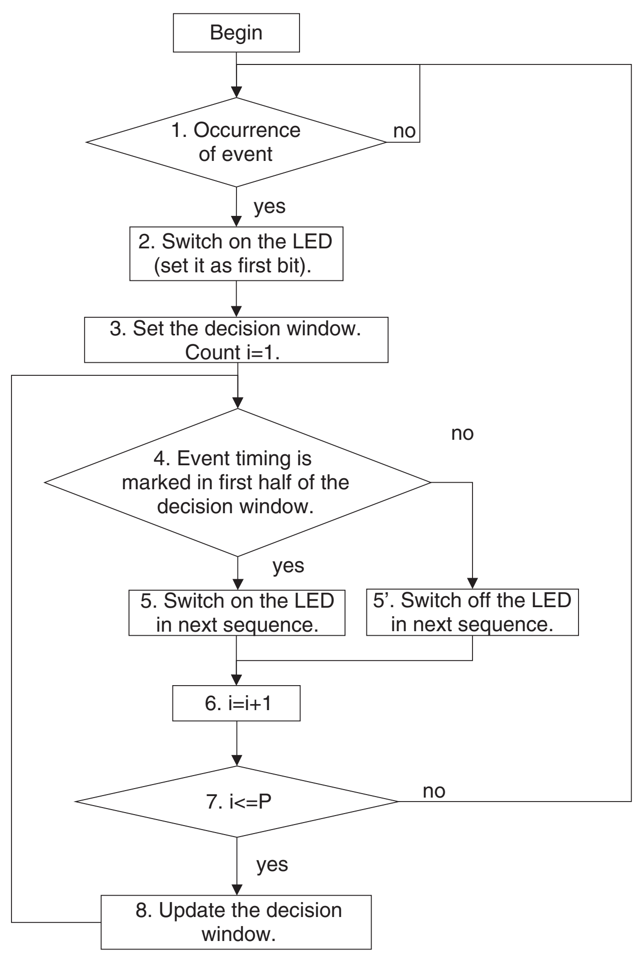


Fig. 2. Flow chart for sending the event timing by flashing an LED.

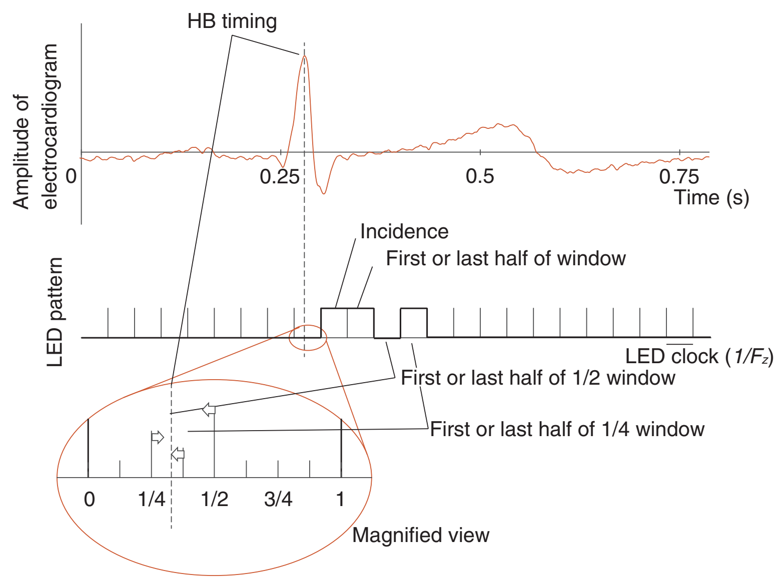


Fig. 3. Example of LED flashing patterns. The LED is switched on immediately as the first bit of the packet after the event detection. The precise event timing is marked on the LED clock frame (see magnified view). The LED pattern from the second bit is determined according to this marked location.

where T_{min} is the shortest term of the HB interval and F_z is the capturing speed of the camera (which is the same as the flashing frequency of the LED). This ET encoding is more efficient than directly transferring the HB time interval under the condition of

$$T_{max} - T_{min} > 2/F_z, \quad (2)$$

where T_{max} is the longest term of the HB interval.

3. Demonstration and comparison

The ET encoding was implemented in our HR monitoring system. The unit was custom-built and can be attached to "hitoe" sensing fabric developed by Toray Industries, Inc. and NTT. It samples an electrocardiogram signal with 500 Hz and 10 bits of resolution. A microcomputer installed in the unit searches for the HB timing and utilizes 5 bits (five on/off flashes of an LED) to send one HB interval.

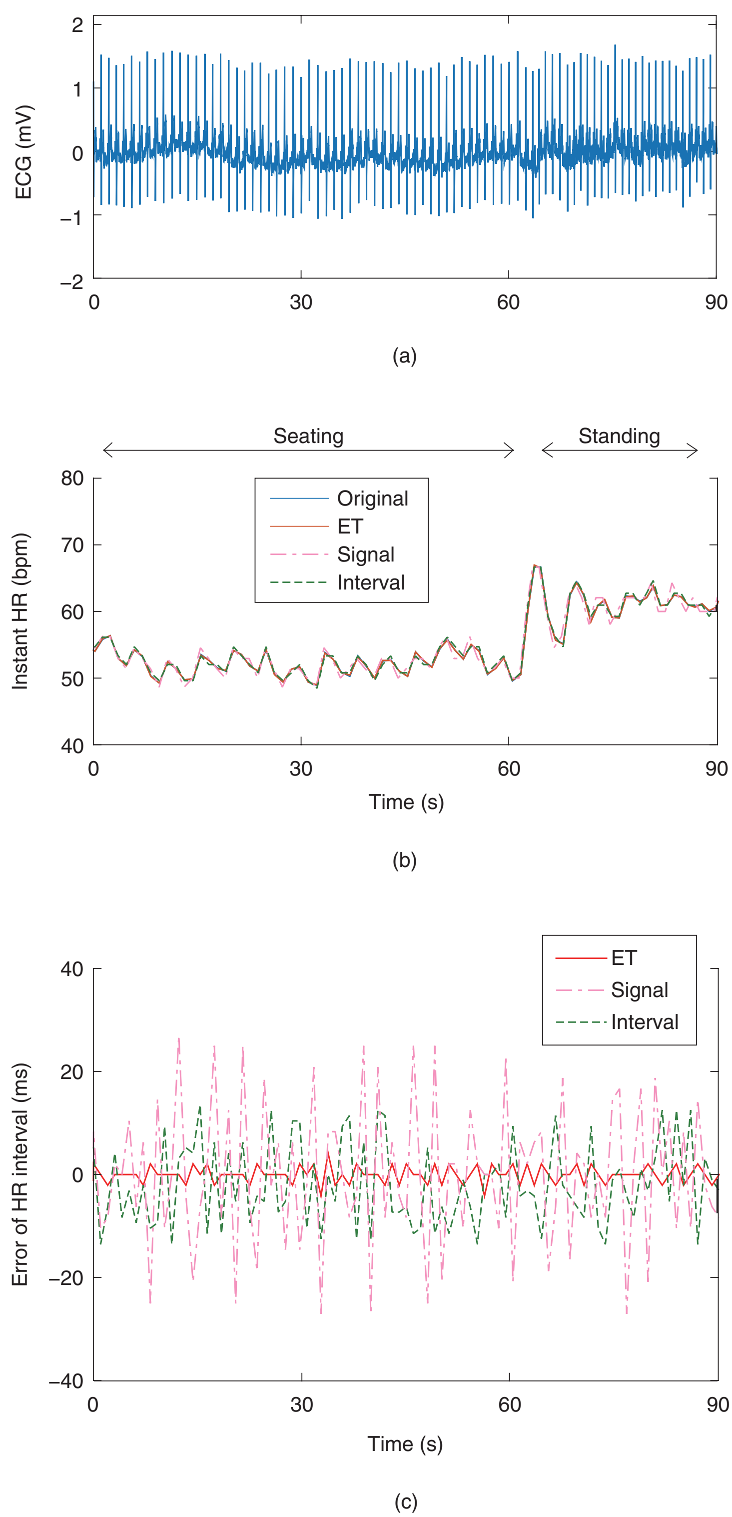
A comparison between the HR observed from direct monitoring and the HR decoded from the LED flashing patterns captured by the camera is shown in **Fig. 4**. HB intervals were calculated for HRs obtained by using four different methods: an HR extracted from the original waveform; an HR transferred by the interval encoding method; an HR reconstructed using an event signal (the same as using only the first signal in ET encoding); and an HR decoded from ET encoding. When 5 bits of data were transferred from the unit, ET encoding gave an almost identical HR.

4. Future development

This article explained efficient encoding methods that can be used in OCC with a low-frame-rate image sensor. We introduced ET encoding, which sends the rough timing of the HB in the first signal and refines its location. Theoretically, ET encoding can send the HR with better resolution than directly sending the interval data in many cases.

We implemented ET encoding in a custom-made electrocardiogram sensor. The results showed that ET encoding transferred HRs with higher resolution when the same bit/beat was used. Concerns that the visible light might be irritating to the human eye can be allayed by using a near-infrared LED.

This system will be implemented in the future to obtain HR data and will be particularly useful for evaluating health risks. Since the system utilizes a common camera, it can be combined with natural image analysis. In addition, data transferrable by ET encoding are not limited to HR. Other data such as spikes in neuronal activity can also be transferred by ET encoding. Further research will open up new possibilities of OCC.



ECG: electrocardiogram

Fig. 4. (a) Waveform of electrocardiogram. (b) Results for HRs, extracted from original waveform; HRs reconstructed using event signal (same as using only first signal in ET encoding); and HRs decoded from ET encoding at 5 bit/packet. From the data, we can trace the activity of participants who stood up from a seated posture. (c) Error between HRs observed from direct monitoring and the HR decoded from different methods. An almost identical HR was obtained with ET encoding.

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Path Loss Model to Evaluate Interference for Small Cells between Different Floors

Motoharu Sasaki, Minoru Inomata, Wataru Yamada, Naoki Kita, Takeshi Onizawa, Masashi Nakatsugawa, Koshiro Kitao, and Tetsuro Imai

Abstract

NTT Access Network Service Systems Laboratories and NTT DOCOMO have been carrying out joint research and development (R&D) toward construction of the fifth-generation mobile communications system (5G). This article presents a path loss model developed as one of our R&D activities.

Keywords: propagation, 5G, high frequency band

1. Introduction

NTT Access Network Service Systems Laboratories and NTT DOCOMO have been conducting a joint study toward development of the fifth-generation mobile communications system (5G). The results of measurements carried out jointly made it possible to clarify the path loss characteristics of the indoor environment in the high frequency band. This article presents the developed path loss model.

2. Path loss model

Frequency allocation of 5G, particularly the high frequency bands above 6 GHz, will be discussed at the World Radiocommunication Conference to be held in 2019. To discuss the appropriate frequency allocation, it is important to evaluate the interference between 5G systems and other existing systems. In the interference evaluation, it is necessary to understand the path loss (attenuation of the radio wave) in order to understand the interference power.

Path loss varies depending on the frequency, so it is essential to construct a path loss model in the frequency band that will be used. It is assumed that the high frequency band above 6 GHz will be used for 5G, and therefore, the standardization group 3rd Generation Partnership Project (3GPP) is standardizing the path loss models of the high frequency band [1].

In 3GPP, office environments are assumed as the indoor small cell scenarios, but the path loss model that can be used in that environment is only for a single floor (the same floor). In order to accurately evaluate interference, an evaluation of inter-floor interference [2] is also required (**Fig. 1**). NTT Access Network Service Systems Laboratories has developed a path loss model for evaluating inter-floor interference for a wide range of frequencies as part of efforts to realize various wireless communication systems.

3. Prediction results produced with developed path loss model

To understand the inter-floor interference of indoor small cells in an office environment, we measured path loss using five frequency bands (0.8, 2.2, 4.7, 26.4, and 37.1 GHz), including the bands above 6 GHz in a multistory building of NTT DOCOMO (from the third to sixth floors). As a result, we clarified

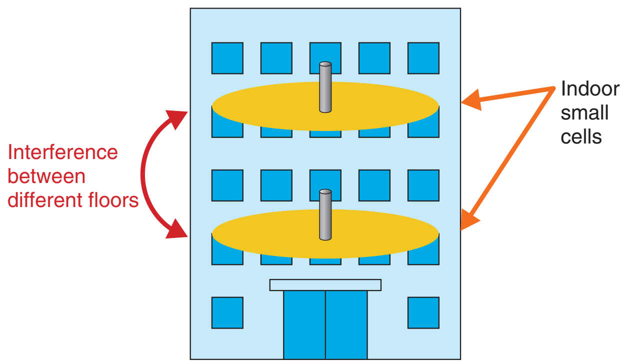

Fig. 1. Interference between different floors in indoor small cells.

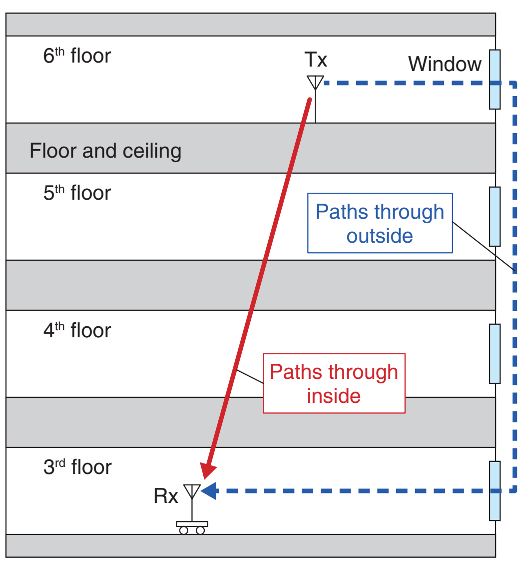

Fig. 2. Dominant paths between different floors.

that the path loss characteristics between different floors were represented by two dominant propagation paths inside and outside the building in a wide frequency band (**Fig. 2**). Here, the propagation path inside the building is the path transmitted through the floors (and ceilings) between the transmitter (Tx) and the receiver (Rx). The propagation path outside the building is the path that is diffracted at the window frame of the Tx floor, propagated outside the building, which then re-enters from the window of the Rx floor. The propagation path inside the building attenuates due to transmission loss caused by ceilings and floors, and the propagation path outside the building attenuates because of the diffraction loss at the window.

The results of calculating the path loss using the proposed model for these two dominant paths are shown in **Fig. 3(a)**, and the results of measuring the path loss between different floors are shown in **Fig. 3(b)**. The measurement results show the median values of path loss at each floor. The value is normalized by the path loss when the Tx and Rx are set on the same floor, and it therefore represents the floor penetration loss when the Tx and Rx are on different floors.

The calculation results in Fig. 3(a) show the path loss of the path inside the building transmitted through floors when varying the floor thickness *w*, and that of the path outside the building that is diffracted at the window frame. The path losses are calculated from 0.1 GHz to 100 GHz. In the measurement environment, the thickness of the floor material was 1.5 m per floor. It can be seen that the transmission loss increases rapidly as the floor thickness increases (that is, as the distance between floors

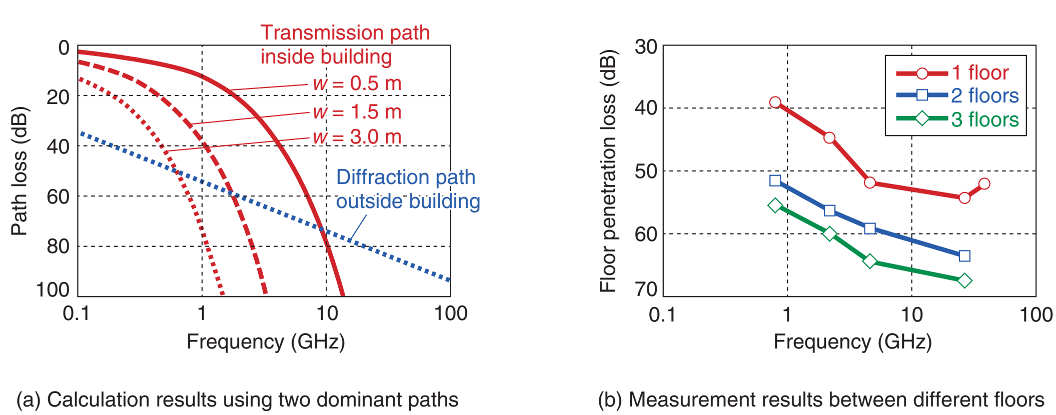

Fig. 3. Results of calculating and measuring path loss between different floors.

increases) or as the frequency increases.

In contrast, the diffraction loss of the path outside the building increases gently with respect to the frequency increase. Therefore, when the frequency is low or the distance between floors is small, the path inside the building (transmission path) becomes dominant, and when the frequency is high or the distance between floors is large, the path outside the building (diffraction path) becomes dominant.

The frequency dependence of the measurement results in Fig. 3(b) can be explained by using the two dominant paths. The path loss for a distance consisting of one floor level increases sharply as the frequency increases up to 4.7 GHz, but over 4.7 GHz the path loss increases gently. Also, in the case of two or three floors, the path loss increases gently with respect to the frequency increase. It is thought that the path inside the building (transmission path) is dominant up to 4.7 GHz at a distance of one floor level (e.g., the distance between the fifth floor and the sixth floor), and the path outside the building (diffraction path) is dominant under the other conditions.

As discussed above, when the two dominant paths are used, it is possible to express the path loss characteristics in a wide frequency band. From this result, for example, when base stations for indoor small cells are installed near a window, it is necessary to pay attention to the fact that interference between floors becomes especially large.

4. Future overview

This article presented a developed path loss model that can represent the path loss characteristics between different floors. The proposed model is suitable for evaluating inter-floor interference of indoor small cells. We expect that the model will be utilized for 5G, which is a key topic in the research, development, and standardization in the wireless communication field worldwide. A paper describing the proposed model won the Best Paper Award at the 2016 International Symposium on Antennas and Propagation (ISAP 2016). Please refer to the paper [3] for more detailed results.

In order to contribute to the construction of various wireless communication systems, we intend to actively engage in the modeling of propagation phenomena for a wider range of frequencies and environments.

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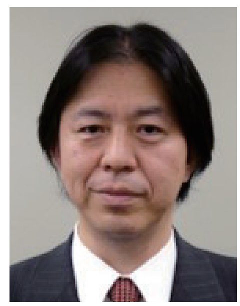

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Report on Progress of ITU-T Study Group 3 at the World Telecommunication Standardization Assembly 2016 (WTSA-16)

Memiko Otsuki

Abstract

The World Telecommunication Standardization Assembly 2016 (WTSA-16) was held in Yasmine Hammamet, Tunisia, from October 25 to November 3, 2016. The following is an outline of discussions on ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) Study Group 3 covered at WTSA-16.

Keywords: WTSA, ITU-T, SG3

1. Outline of ITU-T Study Group 3

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Study Group 3 (SG3) is a unique study group; it is the only study group in ITU-T dealing with international standardization of non-technical aspects such as tariff settlement and economic policies. Traditionally, SG3's main role was to establish standards for tariffs for telecommunications, such as coming up with the principles of tariff settlement or making recommendations aimed at reducing international roaming rates. In the past few years, however, more and more proposals have been made to study themes that go beyond the framework of telecommunications, or themes concerning domestic regulations and policies. These proposals have mainly been coming from members from developing countries, and the discussions on such topics have been heated at the meetings.

The discussions at the World Telecommunication Standardization Assembly 2016 (WTSA-16) [1], which is the supreme decision-making body of ITU-T, were no exception, and many of the developed countries opposed many of the SG3-related proposals presented by developing countries. The discussions and results are introduced in the following section, along with points to be noted in future SG3 activities.

2. Discussions at WTSA-16 relevant to SG3

The discussions relevant to SG3 covered a range of issues from specific technical topics to the SG3 study mandates. They are briefly described here.

2.1 Change of mandate

The term for the domain of study of each SG is a *mandate*. As mentioned, in the past few years, developing countries have been increasingly vocal in expressing their desire for ITU-T to make recommendations in order to justify domestic regulations or policies. At WTSA-16 also, Russia and the Arab states proposed adding the study of *regulatory* issues. However, the United States, western European countries, and Japan opposed the addition of this study theme, saying that regulatory issues are solely domestic issues. As a result, the mandate of SG3 was defined as *International telecommunication/ICT (information and communication technology) policy and economic issues and tariff and accounting matters (including costing principles and methodologies)*.

Table 1. Approved recommendations.

Recommendation no.	Subject of recommendation	Outline
D.52 [New]	Establishing and connecting regional Internet exchange points to reduce costs of international Internet connectivity	Recommendation ITU-T D.52 "Establishing and connecting regional Internet exchange points (IXPs) to reduce costs of international Internet connectivity" guides regional collaboration to establish central hubs or IXPs that enable local Internet traffic to be routed locally, saving international bandwidth and reducing the costs of international Internet connectivity.
D.53 [New]	International aspects of universal service	Recommendation ITU-T D.53 "International aspects of universal service," while recognizing the sovereign right of Member States to define and regulate their universal service/access policies, proposes general outlines to guide governments and regulators in their tasks and management functions regarding universal service funds in a globalized digital environment.
D.97 [New]	Methodological principles for determining international mobile roaming rates	Recommendation ITU-T D.97 "Methodological principles for determining international mobile roaming rates" proposes possible approaches to the reduction of excessive roaming rates, highlighting the need to encourage competition in the roaming market, educate consumers and consider appropriate regulatory actions such as the introduction of caps on roaming rates.
D.261 [New]	Regulatory principles for market definition and identification of operators with significant market power - SMP	Recommendation ITU-T D.261 "Regulatory principles for market definition and identification of operators with significant market power" proposes principles and guidelines to assist countries in defining and identifying significant market power in the telecommunications sector.
D.271 [Modified]	Charging and accounting principles for NGN	ITU-T Recommendation D.271 sets out the general principles and conditions applicable by administrations for the capability to transport Internet protocol (IP) packets over IP-based networks between standards-based interfaces and the services that they support. *Revision adds/deletes part of description on charging parameters.

Source: ITU Journal, Vol. 47, No. 1, 2017

NGN: Next Generation Network

The US and western European countries further insisted that study themes be limited to international issues, and the title of SG3 was also agreed to be ITU-T Study Group 3: Tariff and Accounting Principles and International Telecommunication/ICT Economic and Policy Issues, and by adding the word *international*, it was mandated that SG3 is not to discuss solely domestic issues [2].

2.2 Approval of five recommendations

Five recommendation proposals (four new and one revision) were submitted to WTSA-16 and were all approved (**Table 1**). However, the US, Australia, Germany, Canada, and others pointed out that D.52, D.53, and D.261 were domestic issues, and the recommendations were adopted with reservations from the opposing countries [3].

2.3 Compiling the new resolutions

At WTSA-16, the RCC (Russian regional group) proposed a resolution stating that the ITU-T should get involved in studying all manners of policies for consumer protection in telecommunications/ICT, including fair competition, business models, quality assurance, establishment of reliability, and the assurance of security. The developing countries supported this, but the developed countries, including Japan, opposed it, pointing out the broadness of the scope of consumer protection, and that many of the issues such as quality assurance and security would be redundant with the existing work of ITU-T. As a result, the content was amended to read "to resolve that ITU-T Study Group 3……within their mandates, should carry out studies, including on standards for the protection of consumers and users of telecommunication/ICT services," and it was newly approved as *Studies concerning the protection of users of telecommunication/information and communication technology services* (New Resolution 84) [4].

2.4 International mobile roaming (Resolution 88)

Ever since the bill shock issue, which refers to receiving unexpectedly high mobile phone bills, began to surface, SG3 has been considering establishing a recommendation for lowering international mobile roaming rates. However, some members voiced their concern that the existing recommendation was not being fully utilized, and at WTSA-16, the CITEL (American regional group) proposed a new resolution to execute D.98 (Charging in international mobile roaming service). D.98 was approved in 2012; it recommended increased transparency of rates, provision of alternate plans, and appropriate regulatory measures. The new Resolution D.97 on international roaming is listed in Table 1; Resolution 88 encourages each member state to execute D.98, which had been compiled previously.

2.5 Mobile financial service (Resolution 89)

There are reportedly 2 billion unbanked people in the world. This means they remain outside of the banking system. Providing access to financial services to these people is referred to as financial inclusion. In ITU-T also, a focus group to discuss digital financial services was established in June 2014, and its target was to expand access to financial services through the use of mobile money. In SG3, some members expressed the desire to take leadership in studying this issue, and work is being done to compile recommendations that encourage countries to introduce competition principles and regulations of fees for service transactions.

However, more proposals were put forth from developing countries to include, for example, the issue of granting a license to financial service providers in SG3 recommendations, which is clearly the jurisdiction of financial authorities, and this has become a contentious issue. In WTSA-16, the Arab and African countries proposed a new resolution on “Promoting the use of information and communication technologies to bridge the financial inclusion gap” and resolved to gain the cooperation of telecom and financial authorities. At the same time, it was agreed to avoid redundancy with the work of other standardization bodies and to have the study carried out within the scope of the ITU mandate dealing with telecommunications. The progress in the study on mobile financial services is to be reported at the annual Board meeting and to WTSA in 2020.

2.6 Over the top (OTT) players and services

The activities of OTT players who are delivering content such as video and music and providing voice or messaging services have been gaining more prominence recently. Some members of SG3 concerned with the economic impact of these OTT players on network operators proposed making recommendations on the definition of OTT and the principles of regulation, and a rapporteur group was created to discuss specifics.

At WTSA-16 also, a new resolution was proposed by the African countries that seeks to resolve the OTT’s impact in an appropriate way. In the meeting, there were severely conflicting opinions between developed countries—primarily the United States—and the African and Arab countries on the scope of service the resolution covers, and the ensuing discussion was difficult. The developed countries of the West wanted to avoid subjecting a wide range of services to the resolution and also wanted to limit its scope to voice service and messaging service operators that use public numbering resources (E.164). The African countries that wanted to include more general OTT services strongly opposed this, and consensus was not reached by the end of the session. Multiple official and unofficial meetings were held, and as a result, while a resolution on OTT services was deferred, as a compromise, additions were made to the mandates of SG2 and SG3 of Resolution 2, adding “Study of the economic and regulatory impact of the Internet” to the mandate of SG3.

3. Future development

In addition to the topics above, study questions of each SG in the next study period were approved at WSTA-16. The questions for SG3 are listed in **Table 2**. The field of study covers a wide range, and as time changes, one can see it is no longer an SG dealing with telecommunications tariffs. However, it should be cautioned that this shift of the agenda has been driven by the developing countries. With SG3 in particular, the profile of attendees has changed dramatically, with over 70% now from developing countries, and a large number of them are from regulatory agencies. Most of the study agendas were proposed by developing countries, which have unique issues such as the lack of competition among private companies. There is also less accumulation of know-how to set regulations. For this reason, rather than solving international issues through standardization, there is an increasing tendency to attempt to resolve their own domestic issues through international agreements.

With this type of agenda proposal, the developed countries expressed the view that these issues have already been resolved through regulatory/policy frameworks or agreements among operators, and that issues unique to developing countries should be dealt with by ITU-D*, not ITU-T. The standard response

* ITU-D: ITU Telecommunication Development Sector; its role is to promote utilization and development of ICT in developing countries.

Table 2. SG3 questions.

Questions	Title
Q1/3	Development of charging and accounting/settlement mechanisms for international telecommunications services using next-generation networks (NGNs), future networks, and any possible future development, including adaptation of existing D-series Recommendations to the evolving user needs
Q2/3	Development of charging and accounting/settlement mechanisms for international telecommunications services, other than those studied in Question 1/3, including adaptation of existing D-series Recommendations to the evolving user needs
Q3/3	Study of economic and policy factors relevant to the efficient provision of international telecommunication services
Q4/3	Regional studies for the development of cost models together with related economic and policy issues
Q5/3	Terms and definitions for Recommendations dealing with tariff and accounting principles together with related economic and policy issues
Q6/3	International Internet connectivity including relevant aspects of Internet protocol (IP) peering, regional traffic exchange points, cost of provision of services and impact of transition from Internet protocol version 4 (IPv4) to Internet protocol version 6 (IPv6)
Q7/3	International mobile roaming issues (including charging, accounting and settlement mechanisms and roaming at border areas)
Q8/3	Alternative calling procedures and misappropriation and misuse of facilities and services including calling line identification (CLI), calling party number delivery (CPND) and origin identification (OI)
Q9/3	Economic and regulatory impact of the Internet, convergence (services or infrastructure) and new services, such as over the top (OTT), on international telecommunication services and networks
Q10/3	Definition of relevant markets, competition policy and identification of operators with significant market power (SMP) as it relates to the economic aspects of international telecommunications services and networks
Q11/3	Economic and policy aspects of big data and digital identity in international telecommunications services and networks

Source: https://www.itu.int/en/ITU-T/studygroups/2017-2020/03/Pages/questions.aspx

Table 3. SG3 Chairman and Vice-chairmen.

SG3: Tariff and accounting principles and international telecommunication/ICT economic and policy issues		
Chairman	Seiichi TSUGAWA	Japan
Vice-chairmen	Joséphine ADOU BIENDJUI	Côte d'Ivoire
	Mohammad Ahmad ALMOMANI	Jordan
	Abraao BALBINO E SILVA	Brazil
	Liliana Nora BEIN	Argentina
	Alexey BORODIN	Russian Federation
	Adel DARWISH	Bahrain
	Aminata DRAME	Senegal
	Muneer ELMAKI	Sudan (Republic of the)
	Byoung Nam LEE	Korea (Rep. of)
	Karima MAHMOUDI	Tunisia
	Raynold MFUNGAHEMA	Tanzania
	Ahmed SAID	Egypt
	Dominique WURGES	France

Source: http://www.itu.int/net4/ITU-T/lists/mgmt.aspx?Group=3

from participants from developing countries was that the ITU-D cannot make recommendations. Consequently, another issue that emerged at WTSA-16 was determining how ITU should deal with issues that developing countries are trying to resolve through compilation of international recommendations, and how they should form a consensus. In SG3, although their mandate has been limited to international issues through revision of Resolution 2, many of the vice-chairs are from developing countries (**Table 3**), so this tendency may manifest more strongly. Even broader development of the discussions is envisaged going forward, including the economic aspects of telecommunications and how regulations should be established. Therefore, I think we need to be clearly conscious of what the role of our company and of Japan should be in our endeavors.

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Report on NTT Group Exhibits at CeBIT 2017—Showcasing Cutting-edge Use of ICT at the World's Largest Information Technology Trade Fair

Kei Karasawa

Abstract

The NTT Group exhibited at CeBIT 2017, which ran for five days (March 20–24, 2017) in Hanover, Germany. In its first participation in 12 years, NTT showcased examples of its cutting-edge use of information and communication technology in a variety of industrial fields. The exhibits were presented in an easily comprehensible manner and were highly appreciated by visitors. This article introduces the main exhibits and visitors' responses to them.

Keywords: ICT, Internet of Things, artificial intelligence

1. Objective of exhibiting at CeBIT 2017

The NTT Group had a booth at CeBIT 2017 for the first time in 12 years in order to introduce digital transformation solutions offered by NTT Group companies, which have been expanding their global business. NTT sought to make the exhibits easy for anyone to understand. For example, it offered interactive demonstrations that enabled visitors to directly appreciate the new value that digitization offers, and presented information and communication technology (ICT) use cases in videos in three languages (English, German, and Japanese) to help visitors understand the advantages of selecting the NTT Group as a business partner. The result was an uninterrupted flow of visitors up to the last day, totaling more than 5000 people.

Under the theme "d!conomy – no limits," which had been adopted since 2015, CeBIT 2017 exhibited the latest ICT technologies such as digital transformation, the Internet of Things (IoT), and artificial intelligence (AI). It is noteworthy that Japan became a partner country in 2017, when German Chancellor Angela Merkel and Japanese Prime Minister Shinzo Abe jointly announced the Hanover Declaration, under which the two countries agreed to jointly formulate international standards and undertake research and development (R&D) in cutting-edge technologies such as IoT and AI. The declaration acknowledged Japan's open stance regarding the use of technology as one area in which Germany considers Japan to be outstanding. NTT, for its part, exhibited a number of trailblazing uses of ICT in areas where ICT had been slow to penetrate, such as sports and culture. The company believes that through its CeBIT exhibits, it was able to demonstrate the group's ability to provide a wide range of technologies, not limited to telecommunications.

2. Overview of NTT Group exhibits at CeBIT 2017

The NTT Group exhibited at several sites, including the business security zone and partner booths.

The largest site was the NTT Group booth inside the Japan Pavilion. Exhibited there were new work- and life-styles made possible through the use of ICT, including path-forging activities in areas that are attractive to many people, such as sports and culture, and broad-ranging activities that cut across a variety of industries supporting Japan's economy [1]. This article introduces the NTT Group's major exhibits.

2.1 Sports zone

The NTT Group is pursuing digital transformation, even in fields where the human senses play important roles such as sports.

(1) Application of IoT to sports

For the last two years, Dimension Data, one of the NTT Group integrators, has been providing a service for participants in bicycle races. The service offers various kinds of data based on the position of the user's bicycle, which are obtained from a GPS (global positioning system) device installed under the bicycle saddle. For example, it can provide information about the cyclist such as his/her speed, altitude, and exact position on a map, as well as strategic data for team management such as distances between competitors. The provision of such information during live coverage of bicycle races has enhanced the realistic sensations experienced by viewers watching the television (TV) coverage of the event. Dimension Data is considering expanding the service to include transmission of the physical conditions of cyclists, for example, the degree of fatigue, in real time using sensors installed in their clothing (**Photo 1**).

Photo 1. Real-time sensing of cyclists' physical conditions.

This will be made possible through the use of the wearable sensing fabric "hitoe," which is developed jointly by NTT and Toray Industries, Inc. The fabric can be woven into a uniform so that accurate cardiogram and electromyogram data can be obtained without causing any discomfort to the wearer. Thus, the physical condition of a cyclist can be measured even during a race. We believe that, if TV watchers can understand the physical status of cyclists while watching live race coverage, they can develop a sense of unity with individual racers and become more emotionally engaged with the athletes.

At CeBIT 2017, the presenter himself wore a shirt made of "hitoe" and demonstrated that, while cycling, he was able to check his heart rate and degree of fatigue on a bicycle-mounted smartphone. When NTT President Hiroo Unoura introduced this bicycle to Chancellor Merkel and Prime Minister Abe, who are both sports enthusiasts, they showed keen interest (**Photo 2**).

Photo 2. NTT President Unoura (right) introduces "hitoe" technology to Chancellor Merkel and Prime Minister Abe.

Shirts made of "hitoe" have also been worn by drivers participating in car races such as the Indy 500. The drivers have highly praised the shirts, noting that they allowed the drivers to determine what kind of driving practice they needed to do, because they were able to easily and objectively monitor their physical states. (**Photo 3**)

(2) Smart Stadium

NTT also exhibited a Smart Stadium, in which ICT provides new value for spectators at sports events. In this exhibit, a VIP (very important person) room at a stadium was recreated, where the user could order a meal or replay a scene using a tablet connected to the Internet via Wi-Fi*1. This enabled the user to watch a game with the sensation of being in a real stadium

*1 Wi-Fi is a registered trademark of Wi-Fi Alliance.

Photo 3. Indy 500 race driver Tony Kanaan praises his “hitoe” shirt.

Photo 4. Smart Stadium solution enables spectators to watch a game with the sensation of being in a real stadium.

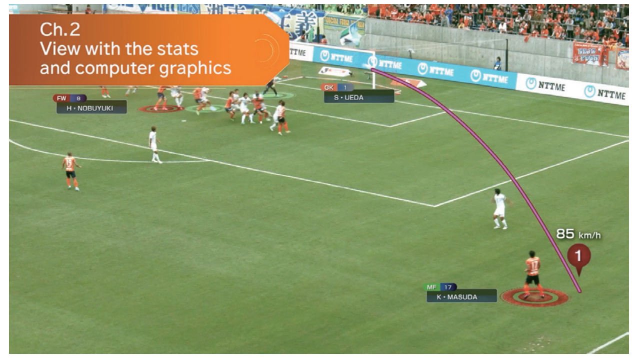

Photo 5. Smart Stadium solution enables spectators in a VIP room to see information on the glass windows overlaid on the real field.

Photo 6. Visitors experienced the sensation of a goalkeeper enabled by VR technology.

while feeling as relaxed as he/she would be when watching TV at home (**Photo 4**). In addition, in cooperation with Panasonic Corporation, NTT exhibited augmented reality (AR), which was achieved by presenting translucent information on the glass windows of the VIP room. This enables spectators of a game to see information overlaid on the real field that is conventionally only available on TV, such as detailed information about their favorite players, team formations, or the off-side line (**Photo 5**). Visitors commented that this would make their watching of a game at a stadium even more enjoyable.

(3) Sports VR

Virtual reality (VR) technology enables the user to take on the perspective of a player on the field. At the NTT booth, visitors were able to experience the sensation of a goalkeeper fielding the ball from a penalty kick by a J-League (Japan Professional Football League) player. They had a high sense of immersion in this experience because not only did they have visual experience through head-mounted displays, but they also wore vibrating devices on their hands and abdomens, which generated vibrations when the virtual ball was received. This proved to be a very popular exhibit. A Euronews correspondent reported enthusiastically on this technology (**Photo 6**).

2.2 Culture (Human Heritage) zone

The NTT Group is also working towards digital transformation through ICT in the area of culture.

(1) Digital archive

In cooperation with the Vatican Apostolic Library, NTT DATA is digitizing the library’s valuable manuscripts for preservation. At CeBIT 2017, NTT displayed a huge bible borrowed from the library and its digitally archived version in parallel. Visitors were able to experience a situation in which they could read the bible on a digital display at any time while looking at the precious real bible alongside. A video showing the painstaking process of archiving was also presented so that visitors could appreciate the significance of this activity. The activity was highly appreciated by those concerned with libraries.

(2) Cultural experience

NTT is experimenting with providing new experiences by fusing *kabuki*, one of the Japanese performing arts, and ICT. It conducted a demonstration in which ICT was used to enable visitors to experience *kumadori*, an unusual style of stage makeup used in kabuki, in which vividly colored makeup is applied to an actor's face. In the demonstration, makeup was not applied to the visitor's face with a real brush. Instead, NTT's angle-free object search technology was used to apply kumadori on an image of his/her face displayed on the screen so that visitors could experience the world of kabuki without discomfort. Specifically, the angle-free object search technology automatically detects the type of mask chosen regardless of the mask's angle. It then uses AR to overlay kumadori on the person's face shown on a display like a mirror, in such a way that the makeup appears to adhere to the face, even when the subject changes his/her facial expression or direction, giving the realistic impression that the cosmetics are actually applied. Those visitors who were well versed in kabuki enjoyed making defiant expressions or gestures with kumadori on their faces, just as if they were actors (**Photo 7**).

Photo 7. Visitors enjoyed having kabuki makeup on their face shown on the screen.

(3) Proposal for new culture

At CeBIT 2017, NTT collaborated with Tokyo National University of Fine Arts and Music in a demonstration of the use of a moving shade to provide an impression of movement of a self-portrait of Vincent van Gogh. Light projection technology known as HenGenTou (Deformation Lamp) created an illusion that the famous painter was eating something. This was an unusual display that could be understood intuitively without the need for explanation, and many visitors stopped and stared in surprise. The Deformation Lamp demonstration attracted a lot of interest, especially from those concerned with art museums as a way to give fresh, dramatic impact to paintings on display.

2.3 Cross Industry Collaborations zone

While manufacturing has traditionally played a central role in Japan's economic development, NTT believes that Japan's high-quality agricultural products and infrastructure services such as its well-developed public transportation systems are playing a larger role in this regard and have become globally competitive in recent years.

In Europe, there are many people running large-scale farms. Visitors from the agricultural field studied NTT's exhibit that showed solutions to several important agricultural issues such as the optimum timing of sowing. In the field of manufacturing, NTT showed a video and exhibited robots from FANUC Corporation. Visitors showed great interest in the precise movements of the robots and real-time analysis of manufacturing conditions made possible by edge computing. In the field of transportation, NTT's exhibit on the use of "hitoe" to support safe driving attracted a lot of interest (**Photo 8**).

Thus, the NTT Group is working to create new value in collaboration with customers by providing ICT across different industrial fields. Videos of the use cases presented at CeBIT 2017 have been posted on YouTube[*2] [2].

2.4 Responses within the NTT Group

The activities introduced above garnered appreciation from employees of the NTT Group's overseas subsidiaries:

"I think that the Smart Stadium solution provided by NTT R&D was amazing and aligned very nicely with the story of the Tour de France and our sponsorship of Team Dimension Data for Qhubeka. Sport is clearly an interesting attraction for visitors to CeBIT and it brought more people into the stand and allowed us to engage with them. I don't think many visitors

*2 YouTube is a registered trademark of Google Inc.

Photo 8. The use of "hitoe" to support safe driving.

understood that the NTT Group was made up of so many powerful brands (NTT DATA, NTT DOCOMO, NTT Communications, and Dimension Data), and so a visit to the stand certainly provided us with a stage to be able to communicate that message to the many visitors."—*Digital Practice, Dimension Data Group*.

"The CeBIT was a fantastic opportunity to show the power of collaboration and solution capacities we have in the NTT Group and to make understandable for so many highly interested visitors what NTT, with all of its powerful brands, can deliver in the era of digitization to help transform society, sports, and industry, as well as creating value for business transformation. From a German perspective of Dimension Data, it absolutely helps to strengthen our brand and awareness in the market, which will also support our business."—*Marketing/PR, Dimension Data Germany*.

"The NTT Communications part of the NTT Group presence at CeBIT was dominated by one item—a replica of the 2017 McLaren Honda Formula 1 racing car which gained lots of interest from visitors to the exhibition and helped improve our brand awareness in Germany, especially those who were not familiar with NTT Communications. The Technology Partnership with McLaren Honda began in July 2016, so the exhibition gave us a chance to explain to people how the use of data is transforming F1 and how NTT Communications is playing a part in that transformation by supplying cloud, network, and cloud management functions. Our network connects the McLaren backbone and supports all of their businesses. Our Enterprise Cloud provides increased capacity and reliability for their apps and services which, for example, helps them simulate all kinds of racing conditions. These technologies support McLaren Honda's efforts to improve performance at each race. Development is continual, and more and more components are being added to the overall solution as we progress. For example, we are developing a race day dashboard for the cloud management platform that will help McLaren's team to optimize performance. We were also able to discuss our R&D activities that can help improve the experience of fans and the F1 team alike. In one instance, an editor from WIRED magazine was fascinated by the possibility of using "hitoe" for monitoring the pit crew and improving their performance, and he especially enjoyed the Smart Stadium demonstration and the saké that was delivered to him one minute after ordering it!"—*Senior Director Marketing, Europe, NTT Communications*.

"I was in charge of the exhibition of the communication robot Sota*3 that introduced the NTT Group booth. Many people stopped at the Sota robots, listening to their talks and taking pictures of them. I also got several questions for actual business cases and introduced the solution proposals and proof-of-concepts for elderly people support and bank reception support. Also, supported languages were another frequent question, which indicates customers from various countries are interested in Sota."—*EMEA Innovation Labs, NTT DATA EMEA Ltd*.

"For DOCOMO, CeBIT provided a great opportunity to showcase our current and future IoT solutions in the fields of agriculture, manufacturing, and transport. Unlike many mobile-specific events, CeBIT visitors come from a wide range of backgrounds across many industries. This not only enabled us to leverage our exposure across industries, but also gave us an opportunity to gain access to creative new ideas on ways our technology can be applied to tackle real-world issues. It was particularly rewarding to be able to work alongside our sibling companies under the same NTT banner, learning about each other's business activities and building a mutual sense of camaraderie. I feel grateful for the new friendships I developed, and have no doubt that opportunities like this will create a synergy that can make us even more efficient and dynamic as a group going forward."—*Public Relations Department, NTT DOCOMO, INC.*

In addition, we have posted visitor interviews on the official NTT channel on YouTube [2].

*3 Sota is a registered trademark of Vstone Co., Ltd.

3. Conclusion

The NTT Group is proposing a B2B2X (business-to-business-to-X) model for creating new services in collaboration with its customer companies. In particular, with 2020 in mind, the group is seeking to continue to use ICT to create new value in such fields as sports and culture. With a wide range of ICT developed by the group centering on NTT laboratories, the NTT Group is endeavoring to provide new value for its customers and to broaden its business horizons.

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He received a B.E., M.E., and Ph.D. from the Department of Information Systems Engineering, Faculty of Engineering, Osaka University in 1994, 1996, and 1999. Since joining NTT in 1999, he has been engaged in research on IPv6 networking, network security, and cloud computing. From 2005 to 2006, he was a visiting scholar in the Applied Cryptography Group at Stanford University, California, USA. He is a member of the Institute of Electronics, Information and Communication Engineers and the Information Processing Society of Japan.

NTT Communications to Deploy 400-Gbit/s Optical Transmission System for Datacenter Network Connections

1. Introduction

NTT Communications Corporation (NTT Com), the information and communication technology solutions and international communications business within the NTT Group, began deploying an ultra-large-capacity, space-saving, and energy-saving 400-Gbit/s (400G) optical transmission system in datacenters for network connection on April 14, 2017. The system raised the transmission capacity of NTT Com's core network above 19 Tbit/s per optical fiber, or more than double the existing capacity. The system utilizes advanced digital-signal processing technology, which is the result of NTT's research and development (R&D).

2. Background

NTT Com achieved its existing 100-Gbit/s-per-channel optical transmission system through the early adoption of digital coherent optical transmission technology in response to rapidly increasing traffic on its core optical fiber network, as well as expanding video data and cloud services. NTT Com has now taken practical steps to upgrade transmission technology to 400G due to ever-increasing network demands for higher speeds and more data, including for 4K/8K and other high-resolution video data, the full-fledged expansion of the Internet of Things, and big-data processing.

3. Features and advantages of 400G system

The main features and advantages of the 400G system, as depicted in **Fig. 1**, are described here.

(1) Top-level energy and space saving (**Fig. 2**)

The new system reduces energy consumption per bit by 75% and space requirements by 80% compared to the existing system. The savings were achieved through a synergistic combination of advanced digital-signal processing technology and 16-nm CMOS (complementary metal-oxide semiconductor) technology. Energy-saving integrated circuits can be constructed rapidly, enabling systems to be quickly deployed even in confined spaces at datacenters.

(2) Higher transmission capacity

The new system achieves more than double the transmission capacity per optical fiber compared to its predecessor system. To generate 400G signals, the system utilizes NTT's research result: 16-quadrature amplitude modulation (QAM) for both phase and amplitude, and sub-carrier multiple transmission.

(3) New optical transport network (OTN) and 400-Gbit/s Ethernet (400GbE) interfaces

In connection with the deployment, NTT Com will offer new optional network services for enterprises, including the sequential launch of OTN interfaces (optical-channel transport unit (OTU)2, OTU2e, and OTU4) primarily for wholesalers and datacenter users, and a 400GbE interface incorporating framing technology compatible with OTUCn, which is the result of NTT's R&D.

(4) Disaggregation architecture

To deliver new services and functions with even greater speed and flexibility, NTT Com will combine software-defined networking (SDN) technologies and disaggregation architecture, which can be redeployed as required according to function or module, replacing existing high-function, all-in-one dedicated equipment.

Going forward, NTT Com and NTT will jointly investigate further possibilities, including the proof

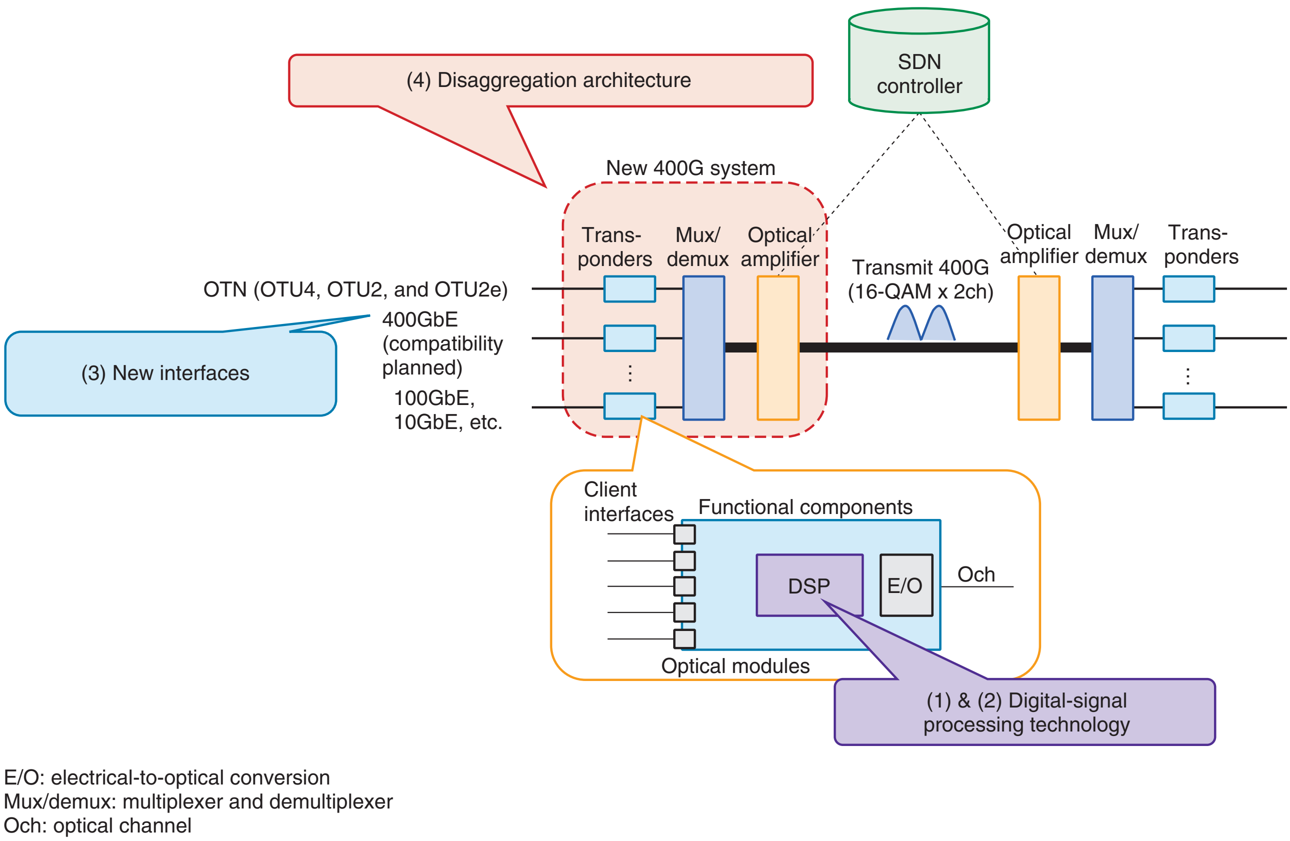

Fig. 1. Main features and advantages of 400G system.

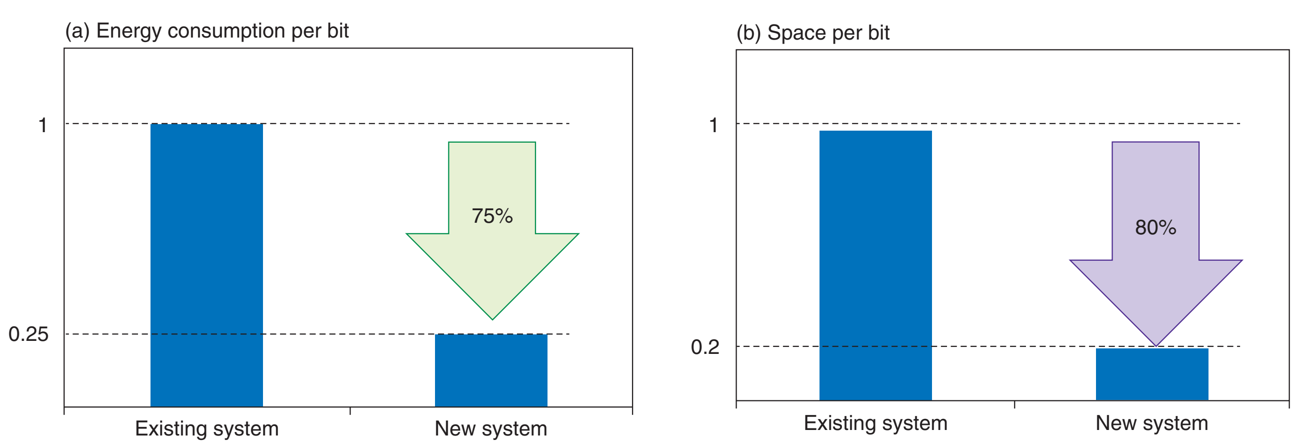

Fig. 2. Energy and space saving effect.

of concept deployment to deliver high-speed Ethernet signals, including 400GbE. Mindful of IEEE (Institute of Electrical and Electronics Engineers) standardization trends, they will pursue increased flexibility and agility for transmission networks by leveraging disaggregated equipment and SDN technologies.

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http://www.ntt.co.jp/news2017/1704e/170407a.html

External Awards

Communications Society: Distinguished Contributions Award

Winner: Hayato Fukuzono, NTT Access Network Service Systems Laboratories
Date: September 21, 2016
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE)

For his contributions as a peer review member for papers submitted to IEICE Transactions on Communications.

JSAI 2016 Annual Conference Award

Winner: Koh Mitsuda and Ryuichiro Higashinaka, NTT Media Intelligence Laboratories; Toshirou Makino, NTT Software Corporation; and Yoshihiro Matsuo, NTT Media Intelligence Laboratories
Date: March 1, 2017
Organization: The Japanese Society for Artificial Intelligence (JSAI)

For "Collection and Analysis of Implicit Information in Chat-oriented Dialogue."
Published as: K. Mitsuda, R. Higashinaka, T. Makino, and Y. Matsuo, "Collection and Analysis of Implicit Information in Chat-oriented Dialogue," JSAI 2016 (The 30th Annual Conference of the Japanese Society for Artificial Intelligence), Fukuoka, Japan, June 2016.

Kambayashi Young Researcher Award

Winner: Kyosuke Nishida, NTT Media Intelligence Laboratories
Date: March 8, 2017
Organization: The Database Society of Japan

For his achievements in authoring published papers such as "Understanding the Semantic Structures of Tables with a Hybrid Deep Neural Network Architecture," "Probabilistic Identification of Visited Point-of-Interest for Personalized Automatic Check-in," and "Improving Tweet Stream Classification by Detecting Changes in Word Probability."
Published as: K. Nishida, K. Sadamitsu, R. Higashinaka, and Y. Matsuo, "Understanding the Semantic Structures of Tables with a Hybrid Deep Neural Network Architecture," Proc. of the Thirty-First AAAI Conference on Artificial Intelligence, San Francisco, CA, USA, Feb. 2017.
K. Nishida, H. Toda, T. Kurashima, and Y. Suhara, "Probabilistic Identification of Visited Point-of-Interest for Personalized Automatic Check-in," Proc. of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, pp. 631–642, Seattle, WA, USA, Sept. 2014.
K. Nishida, T. Hoshide, and K. Fujimura, "Improving Tweet Stream Classification by Detecting Changes in Word Probability," Proc. of the 35th international ACM SIGIR Conference on Research and Development in Information Retrieval, pp. 971–980, Portland, OR, USA, Aug. 2012.

Excellent Interactive Award

Winner: Kyosuke Nishida, Kugatsu Sadamitsu, Ryuichiro Higashinaka, and Yoshihiro Matsuo, NTT Media Intelligence Laboratories
Date: March 8, 2017
Organization: The 9th Forum on Data Engineering and Information Management (DEIM2017)

For "TabNet: A Hybrid Deep Neural Network that Understands the Semantic Structures of Tables."
Published as: K. Nishida, K. Sadamitsu, R. Higashinaka, and Y. Matsuo, "TabNet: A Hybrid Deep Neural Network that Understands the Semantic Structures of Tables," Proc. of DEIM2017, B6-4, Takayama, Gifu, Japan, Mar. 2017 (in Japanese).

SIGGN-101 Best Presentation Award

Winner: Tomohiro Kokogawa, NTT Secure Platform Laboratories
Date: March 11, 2017
Organization: Information Processing Society of Japan (IPSJ) Special Interesting Group on Groupware and Network Services (SIGGN)

For "Visualization and Study of Incident Response Capability of Organizations Based on ISO 22320."
Published as: T. Kokogawa, Y. Maeda, A. Amano, and Y. Kohno, "Visualization and Study of Incident Response Capability of Organizations Based on ISO 22320," IPSJ SIG Technical Report, Vol. 2017-GN-101, No. 23, Mar. 2017 (in Japanese).

The Awaya Prize Young Researcher Award

Winner: Yuma Koizumi, NTT Media Intelligence Laboratories
Date: March 16, 2017
Organization: The Acoustical Society of Japan (ASJ)

For "A Study of Reinforcement Learning for Sound Source Enhancement to Maximize Perceptual Score."
Published as: Y. Koizumi, K. Niwa, K. Kobayashi, and Y. Haneda, "A Study of Reinforcement Learning for Sound Source Enhancement to Maximize Perceptual Score," Proc. of the 2016 Autumn Meeting of ASJ, Toyama, Japan, Sept. 2016.

Young Scientist Award of the Physical Society of Japan

Winner: Yuichiro Matsuzaki, NTT Basic Research Laboratories
Date: March 18, 2017
Organization: The Physical Society of Japan

For his research on robust magnetic field sensing beyond the standard quantum limit.
Published as: T. Tanaka, P. Knott, Y. Matsuzaki, S. Dooley, H. Yamaguchi, W. J. Munro, and S. Saito, "Proposed Robust Entanglement-based Magnetic Field Sensor beyond the Standard Quantum Limit," Phys. Rev. Lett., Vol. 115, 170801, Oct. 2015.
Y. Matsuzaki, X. Zhu, K. Kakuyanagi, H. Toida, T. Shimo-Oka, N. Mizuochi, K. Nemoto, K. Semba, W. J. Munro, H. Yamaguchi, and S. Saito, "Improving the Coherence Time of a Quantum System via a Coupling to a Short-lived System," Phys. Rev. Lett., Vol. 114, 120501, Mar. 2015.
Y. Matsuzaki, S. C. Benjamin, and J. Fitzsimons, "Magnetic Field Sensing beyond the Standard Quantum Limit under the Effect of Decoherence," Phys. Rev. A, Vol. 84, 012103, July 2011.

The Young Scientists' Prize, The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology

Winner: Yasuhiro Fujiwara, NTT Software Innovation Center
Date: April 19, 2017
Organization: The Ministry of Education, Culture, Sports, Science and Technology (MEXT)

For his research on fast graph mining algorithms that support artificial intelligence.

Prize for Science and Technology, Development Category, The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology

Winner: Kazuhide Nakajima, NTT Access Network Service Systems Laboratories; Izumi Sankawa, NTT Electronics; and Shigeru Tomita, NTT Advanced Technology
Date: April 19, 2017
Organization: MEXT

For the development of low bending loss optical fibers.

Prize for Science and Technology, Research Category, The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology

Winner: Akira Fujiwara, NTT Basic Research Laboratories
Date: April 19, 2017
Organization: MEXT

For his research on the ultimate control of electrons in nanostructures, and device applications.

Tsujii-Shigeo Security Paper Award

Winner: Mehdi Tibouchi, NTT Secure Platform Laboratories
Date: April 20, 2017
Organization: Japan Society of Security Management

For "Zeroizing Attacks on Indistinguishability Obfuscation over CLT13."
Published as: J.-S. Coron, M. S. Lee, T. Lepoint, and M. Tibouchi, "Zeroizing Attacks on Indistinguishability Obfuscation over CLT13," Public-Key Cryptography—PKC 2017—the 20th IACR International Conference on the Practice and Theory in Public-Key Cryptography, Amsterdam, The Netherlands, Mar. 2017, pp. 41–58, Springer.

Best Paper

Winner: Kosuke Nakamura, Masahiro Suzuki, Hideyuki Torii, Kazutake Uehira, Kanagawa Institute of Technology; Youichi Takashima, NTT Service Evolution Laboratories
Date: May 9, 2017
Organization: IARIA (International Academy, Research, and Industry Association)

For "Embedding and Detecting Patterns in a 3D Printed Object."
Published as: K. Nakamura, M. Suzuki, H. Torii, K. Uehira, and Y. Takashima, "Embedding and Detecting Patterns in a 3D Printed Object," Proc. of PATTERNS 2017 (The Ninth International Conferences on Pervasive Patterns and Applications), Athens, Greece, Feb. 2017.

IEICE-CS NV Best Presentation Award

Winner: Yosuke Takahashi, Akito Suzuki, and Masayuki Tsujino, NTT Network Technology Laboratories; Noriaki Kamiyama, Fukuoka University; Keisuke Ishibashi, NTT Network Technology Laboratories; Kohei Shiomoto, Tokyo City University; Tatsuya Otoshi, Yuichi Ohsita, and Masayuki Murata, Osaka University
Date: May 11, 2017
Organization: The Technical Committee on Network Virtualization (NV), IEICE Communications Society (CS)

For "Experimental Demonstration of a Flow Mining Based Proactive Network Control Technology on a Wide Area SDN Testbed."
Published as: Y. Takahashi, A. Suzuki, M. Tsujino, N. Kamiyama, K. Ishibashi, K. Shiomoto, T. Otoshi, Y. Ohsita, and M. Murata, "Experimental Demonstration of a Flow Mining Based Proactive Network Control Technology on a Wide Area SDN Testbed," The 18th NV Symposium, Tokyo, Japan, Apr. 2016.

ITU-AJ Accomplishment Award

Winner: Kazuhide Nakajima, NTT Access Network Service Systems Laboratories
Date: May 17, 2017
Organization: The ITU Association of Japan (ITU-AJ)

For his commitment in international standardization activities concerning optical fibers in International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Study Group 15.

Best Paper Award

Winner: Daiki Chiba, Takeshi Yagi, Mitsuaki Akiyama, Kazufumi Aoki, Takeo Hariu, NTT Secure Platform Laboratories; Shigeki Goto, Waseda University
Date: May 19, 2017
Organization: IEICE Communications Society

For "BotProfiler: Detecting Malware-infected Hosts by Profiling Variability of Malicious Infrastructure."
Published as: D. Chiba, T. Yagi, M. Akiyama, K. Aoki, T. Hariu, and S. Goto, "BotProfiler: Detecting Malware-infected Hosts by Profiling Variability of Malicious Infrastructure," IEICE Trans. Commun., Vol. E99-B, No. 5, pp. 1012–1023, May 2016. DOI:10.1587/transcom.2015AMP0001.

Best Paper Award

Winner: Riichi Kudo, B. A. Hirantha Sithira Abeysekera, Yusuke Asai, Takeo Ichikawa, Yasushi Takatori, and Masato Mizoguchi, NTT Access Network Service Systems Laboratories
Date: May 19, 2017
Organization: IEICE

For "User Equipment Centric Downlink Access in Unlicensed Spectrum for Heterogeneous Mobile Network."
Published as: R. Kudo, B. A. H. S. Abeysekera, Y. Asai, T. Ichikawa, Y. Takatori, and M. Mizoguchi, "User Equipment Centric Downlink Access in Unlicensed Spectrum for Heterogeneous Mobile Network," IEICE Trans. Commun., Vol. E98-B, No. 10, pp. 1969–1977, Oct. 2016.

KIYASU-Zen'iti Award

Winner: Tatsuaki Okamoto, NTT Secure Platform Laboratories, and Katsuyuki Takashima, Information Technology R&D Center, Mitsubishi Electric Corporation
Date: June 1, 2017
Organization: IEICE

For "Adaptively Attribute-Hiding (Hierarchical) Inner Product Encryption."
Published as: T. Okamoto and K. Takashima, "Adaptively Attribute-Hiding (Hierarchical) Inner Product Encryption," IEICE Trans. Fundamentals., Vol. E99-A, No. 1, pp. 92–117, Jan. 2016.

Outstanding Paper Award 2016

Winner: Hiroaki Kikuchi, Meiji University, and Katsumi Takahashi,

NTT Secure Platform Laboratories
Date: June 2, 2017
Organization: IPSJ

For "Zipf Distribution Model for Quantifying Risk of Re-identification from Trajectory Data."
Published as: H. Kikuchi and K. Takahashi, "Zipf Distribution Model for Quantifying Risk of Re-identification from Trajectory Data," J. Info. Process, Vol. 24, No. 5, pp. 816–823, Sept. 2016.

Papers Published in Technical Journals and Conference Proceedings

Visual Wetness Perception Based on Image Color Statistics

M. Sawayama, E. H. Adelson, and S. Nishida

Journal of Vision, Vol. 17, No. 5, May 2017.

Color vision provides humans and animals with the abilities to discriminate colors based on the wavelength composition of light and to determine the location and identity of objects of interest in cluttered scenes (e.g., ripe fruit among foliage). However, we argue that color vision can inform us about much more than color alone. Since a trichromatic image carries more information about the optical properties of a scene than a monochromatic image does, color can help us recognize complex material qualities. Here we show that human vision uses color statistics of an image for the perception of an ecologically important surface condition, i.e., wetness. Psychophysical experiments showed that overall enhancement of chromatic saturation, combined with a luminance tone change that increases the darkness and glossiness of the image, tended to make dry scenes look wetter. Theoretical analysis along with image analysis of real objects indicated that our image transformation, which we call the wetness enhancing transformation (WET), is consistent with actual optical changes produced by surface wetting. Furthermore, we found that the WET operator was more effective for the images with many colors (large hue entropy) than for those with few colors (small hue entropy).

The hue entropy may be used to separate surface wetness from other surface states having similar optical properties. While surface wetness and surface color might seem to be independent, there are higher order color statistics that can influence wetness judgments, in accord with the ecological statistics. The present findings indicate that the visual system uses color image statistics in an elegant way to help estimate the complex physical status of a scene.

Metal-organic Vapor-phase Epitaxy of InP-based HEMT Structures with $InAs/In_{0.8}Ga_{0.2}As/In_{0.53}Ga_{0.47}As$ Composite Channel

H. Sugiyama, T. Hoshi, A. El Moutaouakil, and H. Matsuzaki

The 29th International Conference on Indium Phosphide and Related Materials (IPRM 2017), Berlin, Germany, May 2017.

InP-based high electron mobility transistor (HEMT) structures with an $InAs/In_{0.8}Ga_{0.2}As/In_{0.53}Ga_{0.47}As$ composite channel were successfully fabricated by metal-organic vapor-phase epitaxy (MOVPE). We managed to grow highly strained channels at a low temperature of 440ºC. In practical ultra-high-speed HEMT structures with 9-nm barrier-spacer layers, high mobility of around 17,000 cm^2/Vs with a sheet carrier concentration of around $2.5x10^{12}$ cm^{-2} was obtained at room temperature.
