World's First Successful Experiment Using a Quantum Computer for Future Massive Connectivity

Kouki Yonaga
Researcher
Network Research Institute,
Resilient ICT Research Center
Sustainable ICT System Laboratory
National Institute of Information
and Communications Technology

Kenichi Takizawa
Director
Network Research Institute,
Resilient ICT Research Center
Sustainable ICT System Laboratory
National Institute of Information
and Communications Technology

1. Background

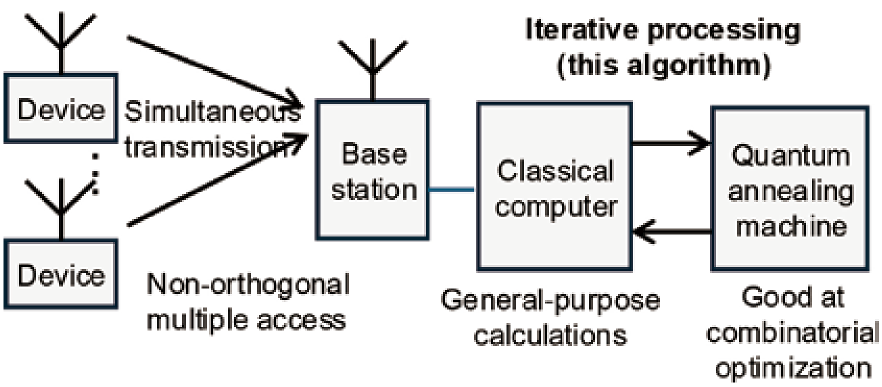
International discussions on next-generation mobile communications systems are underway amid the spread of the fifth-generation mobile communications system (5G). In November 2023, ITU-R Recommendation M.2160[1] was issued describing usage scenarios and functions expected of mobile communications systems for 2030 and beyond. This Recommendation, while extending the three usage scenarios of ultra-high-speed communications, low latency and high reliability, and massive connectivity in 5G, added the three usage scenarios of integrated sensing and communications, use of artificial intelligence (AI), and ubiquitous connectivity. In terms of many-device connectivity, it describes an increase in the degree of connected devices from 106 devices/km^2 in 5G to a range of 10^6 to 10^8 devices/km^2 in next-generation mobile communications systems. This progress is expected to lead to the creation of novel applications in a variety of fields including smart cities, transportation, logistics, healthcare, energy, environmental monitoring, and agriculture. Non-orthogonal multiple access (NOMA)[2] is a technology now attracting attention as a means of improving connectivity by allocating the mobile communications resources of time and frequency to multiple devices while allowing interference between them. When using NOMA on the uplink, signal separation processing is necessary considering the inter-device interference at the base station, but this processing creates an issue in that computational complexity increases exponentially.

2. Signal processing technology using quantum annealing

The quantum annealing machine has recently been attracting attention as a computer that can solve combinatorial optimization problems at high speed. Quantum computers can be broadly divided into "gate-type" and "annealing-type," and an annealing-type of quantum computer is called a quantum annealing machine. Professor Hidetoshi Nishimori of Tokyo Institute of Technology established the theoretical foundation of the "annealing-type" in 1998. Additionally, D-Wave Systems in Canada commercialized the quantum annealing machine for the first time in the world in May 2011. Quantum annealing (QA), which is analogous to the annealing process in metallurgy, is a technique that explores an optimal solution through time evolution using quantum fluctuations. To initiate QA, we set quantum fluctuation dominant to explore diverse solutions. Then, we gradually reduce those quantum fluctuations, guiding QA towards a single solution. By executing this process slowly, QA can achieve the optimal solution.

Quantum annealing machines are designed for solving combinatorial optimization problems but not suited for general-purpose calculations. Signal separation processing in NOMA involves not only large-scale combinatorial optimization problems but also general-purpose calculations such as demodulation and decoding. Therefore, applying QA to NOMA requires the development of a practical method that effectively leverages

■ Figure 1: Signal processing using quantum annealing (when applied to non-orthogonal multiple access)



quantum annealing machines.

At NICT, we have developed a new quantum-digital hybrid algorithm that integrates the quantum annealing machine with classical digital computers[3]. This algorithm enhances computational efficiency and applicability across various areas of signal processing. In this algorithm, we utilize the quantum annealing machine as a sampler that generates diverse solutions. After QA sampling on the order of microseconds, we perform post-processing for the obtained samples using a classical computer. Through this approach, our algorithm can accurately capture the desired probability distribution even with a limited number of samples (Figure 1). Our algorithm offers the advantage of being directly applicable to conventional digital communication systems that include signal processing on the classical computer, such as error-correcting code decoding. Furthermore, as shown in the figure, it can also be applied to sequential processing, where iterative operations are performed between the quantum annealing machine and the classical computer.

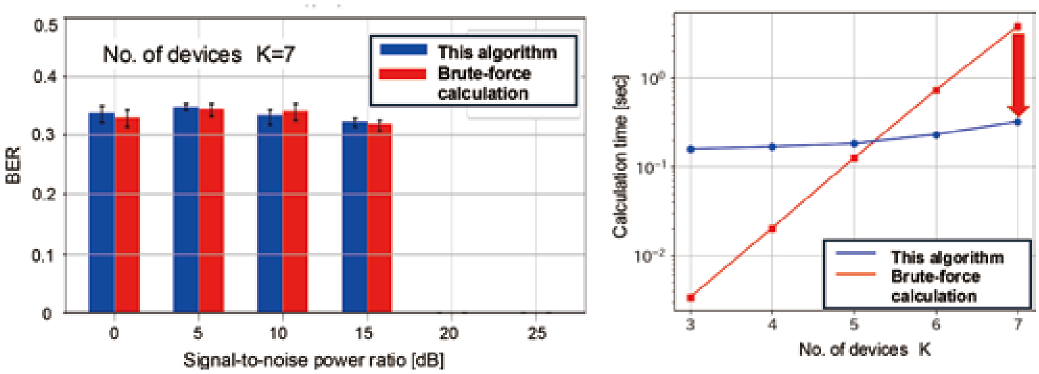
3. Experiment and evaluation

We applied the proposed algorithm to signal separation at a base station in an uplink NOMA system. Let M and K represent the modulation order of transmitted signals and the number of simultaneously connected devices, respectively. Thus, the number of possible received signal combinations is given as M^K, meaning that computational complexity increases exponentially as K grows. Additionally, when K exceeds the number of antennas at the base station, the uplink NOMA system is in an "overloaded state," making the signal separation particularly challenging. While many previous studies have investigated the application of QA to signal separation processing (such as [4] and [5]), our algorithm can be effectively applied to such overload systems.

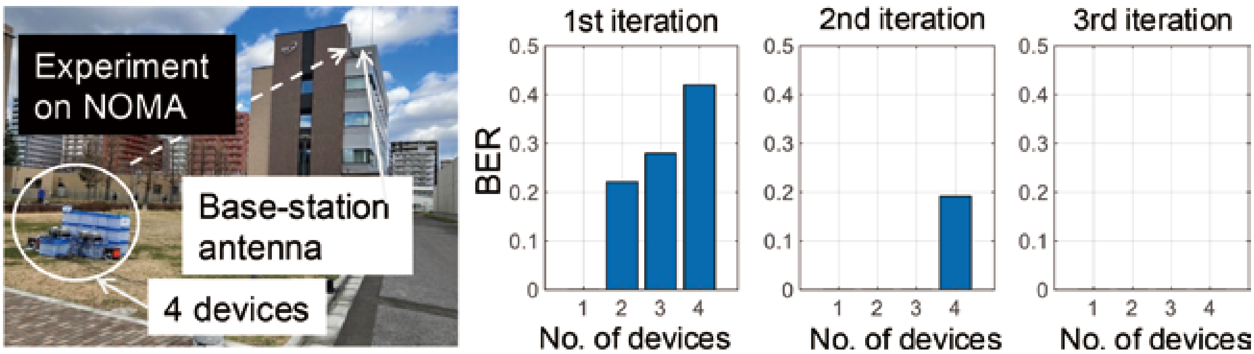
We first evaluated the performance of the proposed algorithm through numerical simulations. We generated transmission signals from multiple devices, superposed them, and simulated the received signal at the base station. Then, we applied the proposed algorithm to signal separation processing. We used the D-Wave quantum annealing machine to obtain samples. The obtained samples were post-processed on a classical computer to calculate the log-likelihood ratio (LLR) of each codeword bit. Finally, error correction decoding and error detection were performed for each device, completing the signal separation process. After error detection, we generated replicas of the received signals for correctly detected devices and subtracted them from the received signal. Then, we performed combinatorial optimization processing using the quantum annealing machine in the iterative process. Annealing time in the quantum annealing machine was set to 20 μs and the number of samplings to 1,000. In our simulation, the transmission signals from the devices were QPSK signals (M = 4, single carrier modulation) and turbo codes were used as error-correcting codes. The number of simultaneously connected devices K per one antenna at the base station was a maximum of 7 and the number of possible received signal combinations for K = 7 was greater than 16,000. Evaluation results showed that the proposed algorithm has comparable separation performance (bit error rate (BER) characteristics) compared with a conventional technique using only a classical computer (Figure 2 left). In addition, the results showed that the calculation time for signal separation processing when using the proposed algorithm (calculated as the integrated value of time required for quantum annealing) could be shortened to approximately 1/10 that when using only a classical computer (Figure 2 right).

After computer simulations, we developed a wireless communication experimental system implementing the proposed algorithm for a base station and demonstrated it outdoors in the field. The multiple devices transmitted QPSK signals (M = 4, single carrier modulation) at the same time and same frequency, and the base station converted the received signals into baseband signals. Then, we estimated radio-wave propagation characteristics (complex numbers) through a reference signal and performed QA samplings using the D-Wave quantum annealing machine. Here, the annealing time was 20 μs and the number of samples was set to 1,000. The number of devices was limited to four units (K = 4) because the purpose here was a proof-of-principle demonstration, and the number of base-station antennas was one. As shown in Figure 3, the results showed that signal separation without error

Figure 2: Evaluation results by computer simulation



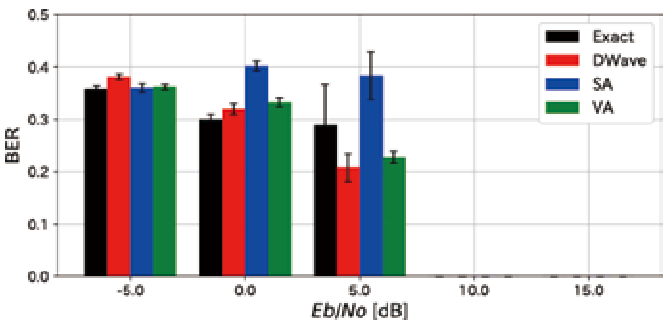
■ **Figure 3: Overview of proof-of-principle demonstration in the field (No. of devices K = 4)**



could be achieved by performing iterative processing three times between the classical computer and quantum annealing machine (signal-to-noise power ratio at the time of this experiment was approximately 26 dB). This demonstration was the world's first successful online experiment on signal separation processing using a quantum annealing machine for uplink NOMA in the field[6].

Furthermore, we are studying the application of the proposed algorithm to 5G New Radio (NR) signals to enhance multi-device connectivity performance[7]. For this purpose, we updated the algorithm to support a CP-OFDM transmission signal and multiple-input multiple-output (MIMO) systems in 5G NR. Figure 4 shows the performance evaluation obtained by the computer simulations. Here, the number of base-station antennas = 2, the number of simultaneously connected devices = 4, subcarrier interval = 15 kHz, and error-correcting code = LDPC. The results revealed that the proposed algorithm using D-Wave (labeled as "D-Wave" in the figure) exhibited BER performance equivalent to the exact calculation results ("Exact" in the figure). The results also demonstrated that the vector annealer ("VA" in the figure) and simulated annealing ("SA" in the figure) could achieve signal separation. Therefore, various types of annealing techniques can be applied to our algorithm. Additionally, we plan to conduct outdoor experiments to validate the algorithm for 5G NR systems.

■ **Figure 4: Example of application to 5G NR signals (computer simulation, number of devices K = 4)**



4. Future outlook

The algorithm proposed in this research is expected to become a fundamental technology supporting next-generation mobile communications systems. Furthermore, in addition to multiple access technologies, it shows promise for application to a variety of fields involving combinatorial optimization calculations such as large-scale beam forming and network optimization. Our goal going forward is the practical implementation of this technology by holding actual field tests and making further improvements to the algorithm.

Acknowledgments

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