Optical Network Technologies for Enabling 5G Services

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Development of the fifth-generation mobile communications system (5G) is underway, with commercialization expected around 2020. In the 5G era, new services (5G services) based on new technologies are anticipated, including distribution of high-definition video, autonomous vehicles enabled by low-latency connections, and data utilization obtained by wide variety of IoT devices. 5G optical networks will also require an array of technologies, as part of the social infrastructure supporting 5G services. As such, Fujitsu is developing technologies for efficient transmission of large volumes of data with low latency, and for automation of complex network management, among others. This paper outlines the challenges pertaining to 5G optical networks and describes the technologies Fujitsu has developed to address these challenges.

1. Introduction

With the implementation of the fourth-generation mobile communications systems (4G), popularization of terminals such as smartphones and tablets has led to the provision of services such as video chat and streaming of music and video. Furthermore, with the spread of cloud services implemented in datacenters (DCs), it is now possible to implement and provide various services rapidly. With these developments, data traffic has been increasing at a rate of 130% per year. To meet this traffic demand, the optical backbone networks between cities and between DCs are operating with 100-Gbps-per-wavelength-class optical transmission equipment.

On the other hand, development is also advancing toward the implementation of the fifth-generation mobile communications system (5G) by 2020. 5G requires new technologies such as high-speed, low-latency communication, and the connection of a wide variety of devices. In the 5G era, new services (5G services) utilizing these technologies will be developed. Such services include, for example, high-definition video distribution and virtual reality (VR), autonomous vehicles and remote-controlled manufacturing equipment, and IoT applications. 5G optical networks will operate as the social infrastructures to support these 5G services. They require the following three main technologies.

1) Optical transceiver technology capable of efficient, high-capacity communication to handle the demand from explosive increases in data traffic.
2) Low-latency network technology for implementing applications such as autonomous vehicles and remote control of manufacturing equipment.
3) Flexible optical network technology and technology to simplify and automate the operation of optical networks to enable various 5G services to be provided efficiently.

Fujitsu is conducting R&D on these optical network technologies to contribute to the expansion of 5G services.

This paper discusses the challenges with 5G optical networks and introduces initiatives at Fujitsu on technologies needed to address them.

2. Issues of 5G optical network

An overview of 5G optical networks is shown in **Figure 1**. With conventional optical networks, telecom providers have used their access networks to provide mobile communication services for smartphones and other devices, and fiber to the home (FTTH) services. In metro networks providing intra-regions connections, edge nodes aggregate these multiplex services to 100

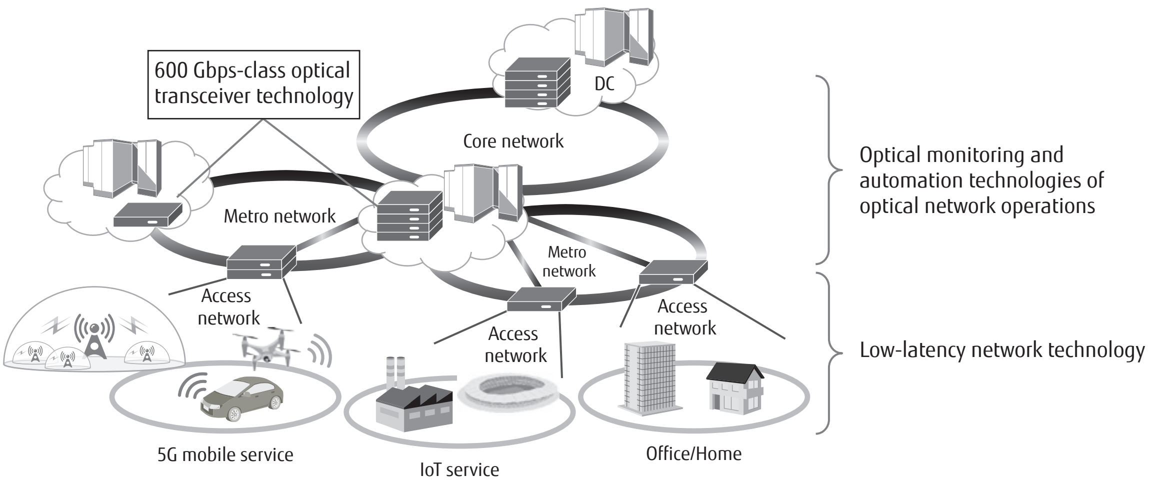


Figure 1
5G optical network overview.

to 200 Gbps-class, high-bit-rate signals. Finally, core networks connect large metropolitan areas and DCs, providing long-distance, high-capacity communication services.

In contrast, in the 5G era, huge amounts of data will be concentrated in DCs to provide services such as high-definition video distribution, autonomous vehicles, and IoT services using large numbers of sensors. As such, data traffic on optical networks is expected to increase sharply not only between end users and DCs, but also between DCs.

To meet this demand of data traffic, high-capacity and efficient optical transceiver technologies are important. Reducing the size and power consumption of optical transceivers is also a major issue, so that communications equipment with increased capacity can be accommodated within the limited space in communications facilities.

Applications requiring very low latency, such as autonomous vehicles and remote medicine, are also being studied. On the other hand, growth of IoT services utilizing sensor data in fields such as manufacturing and agriculture are also expected to accelerate. As such, it is imperative to build a new access packet network integrating wired and wireless technologies able to accommodate traffic with diverse requirements efficiently. How to realize ultra-low latency is a particularly important issue.

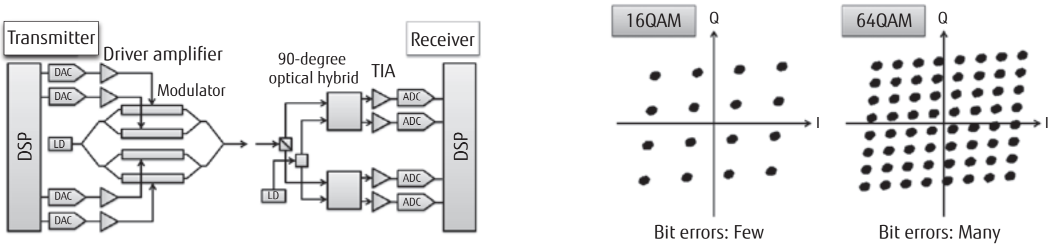
To handle the demand from diverse 5G services, it will be essential to deploy highly flexible optical network devices and to control the network efficiently. To realize such a flexible optical network requires technologies to monitor the state of the network and to change the configurations of devices comprising the network automatically, in accordance with its current state.

In the following sections, we discuss technologies that Fujitsu has developed to address these challenges, including technologies for a 600 Gbps-class optical transceiver, for low-latency networks, for optical monitoring, and for automating optical network operations.

3. 600 Gbps-class optical transceiver technology

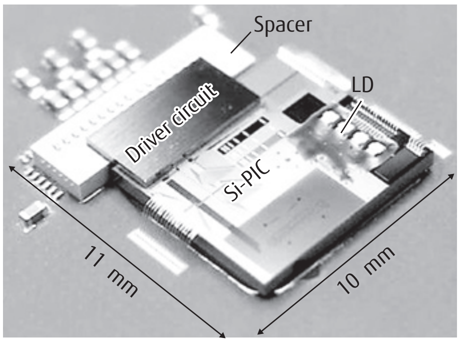
Fujitsu is developing a 600 Gbps-class optical transceiver to support 5G services, using multi-level modulation and compensation technologies to increase capacity, and integrated photonics technologies to increase density and decrease power consumption. To achieve this, modulation methods with higher baud rates and higher-order modulation level than those used before must be used. For example, when compared with those of a mainstream 200-Gbps-per-wavelength optical transceiver, the baud rate would need to be doubled from 32 to 64 Gbaud and the number of bits per symbol would need to increase 1.5 times from 8 to 12 bits/symbol.

The basic architecture of the optical transceiver



(a) Optical transceiver basic architecture

(b) 16QAM and 64QAM signal constellations



(c) 16-channel integrated optical transceiver proto-type

DAC: Digital-to-analog converter
ADC: Analog-to-digital converter
DSP: Digital signal processor
LD: Laser diode
TIA: Transimpedance amplifier
QAM: Quadrature amplitude modulation

Figure 2
Overview of 600 Gbps-class optical transceiver technology.

is shown in **Figure 2(a)**. For the optical transceiver to handle multi-level modulated signals at high baud rates, advances in individual components, such as high-speed digital-to-analog (DA) and analog-to-digital (AD) converters, as well as wide-bandwidth devices are assumed. Major advances in compensation technologies for degradation in signal characteristics due to waveform distortion and noise are also needed.

For example, with high-order multi-level modulation such as 64QAM, even a small amount of waveform distortion can produce considerable degradation in the bit error ratio (BER). The diagram in **Figure 2(b)** is called a signal constellation and shows the positions of symbols in the modulated signal, plotted on a complex plane. When the distance between symbols is small, a small amount of waveform distortion can result in a symbol being incorrectly detected from adjacent symbols, so bit errors can occur more easily. For this reason, highly accurate compensation technology to prevent even a small amount of waveform distortion is needed.

A coherent digital signal processor (DSP) compensates for various degradations on the transmission path, such as wavelength dispersion and fluctuation in polarization. It also compensates for degradation occurring in the transmitter and receiver.

As part of this, both transmitter and receiver are equipped with linear equalizers to compensate for linear distortion. Equalization to generate a signal similar to the desired waveform is implemented with tapped delay lines, computing a convolution on the signal and each tap coefficient. To derive the tap coefficients, an algorithm such as minimum mean square error (MMSE), which minimizes the square of the difference between the measured signal and a reference signal, is used. Applying this equalization technology has made the transmission and reception of 600 Gbps-class optical signals possible.

Next, we describe an integration technology for reducing the size of optical transceivers. As mentioned earlier, space is limited in telecom buildings, so reducing the size of communications equipment is important. Fujitsu is developing an integrated photonics technology to reduce the size and power consumption of 600 Gbps-class optical transceivers.

Earlier optical transceivers have been composed of separate sub-modules and parts such as LiNbO3 modulators (LN modulators) and wavelength-tunable laser modules. In designing the overall module, such structures have the advantage that the performance and reliability of each part can be ensured separately. On the other hand, the size and power consumption of the optical transceiver is constrained by the sizes of individual sub-modules and the electrical and optical connections between sub-modules. For example, an increase in power accompanying an increase in signal speed is a major issue when transmitting signals between sub-modules, and the size and number of devices in the optical components are also major issues.

To resolve these issues, based on Si photonics technology using silicon (Si) substrates as a platform, we are developing a silicon photonic-integrated-circuit (Si-PIC) technology, which enables the integration of optical devices such as semiconductor lasers, optical modulators and photo detectors on a Si substrate.

Integrated photonics using Si-PICs have the following advantages.

1) Each optical device can be miniaturized due to large difference in refractive indices of materials in Si optical wave guides, so Si-PIC devices can be densely integrated.
2) Optical devices can be connected using Si optical wave guides, simplifying and reducing the size of the optical systems.
3) Flip-chip bonding can be used to connect to Si driver circuits for higher density implementation. The use of shorter wiring improves the quality of electrical signals and power supply.

An optical transceiver with these benefits is shown in **Figure 2 (c)**. It uses the integrated photonics technology to implement a densely integrated Si-PIC optical transceiver with 16 channels at 25 Gbps, connected to driver circuits with flip-chip bonding and achieves a density of 363 Gbps/cm^2 (400 Gbps on a 10×11 mm^2 footprint).1) In addition to reducing the size of individual optical devices, we can also expect improvements in device characteristics, such as lower power consumption in an optical modulator driven as a lumped load and higher speed operation in the photodetector due to small capacitance.2)

4. Low-latency network technology

Currently, mobile networks are becoming a centralized radio access network (C-RAN) configuration. In this configuration, conventional base stations (e-Node B: eNB) are being separated into a base station function, implemented as the centralized unit (CU), and a radio antenna function, implemented as the distributed unit (DU). A CU and DUs are connected via the mobile fronthaul (MFH) network (**Figure 3**).

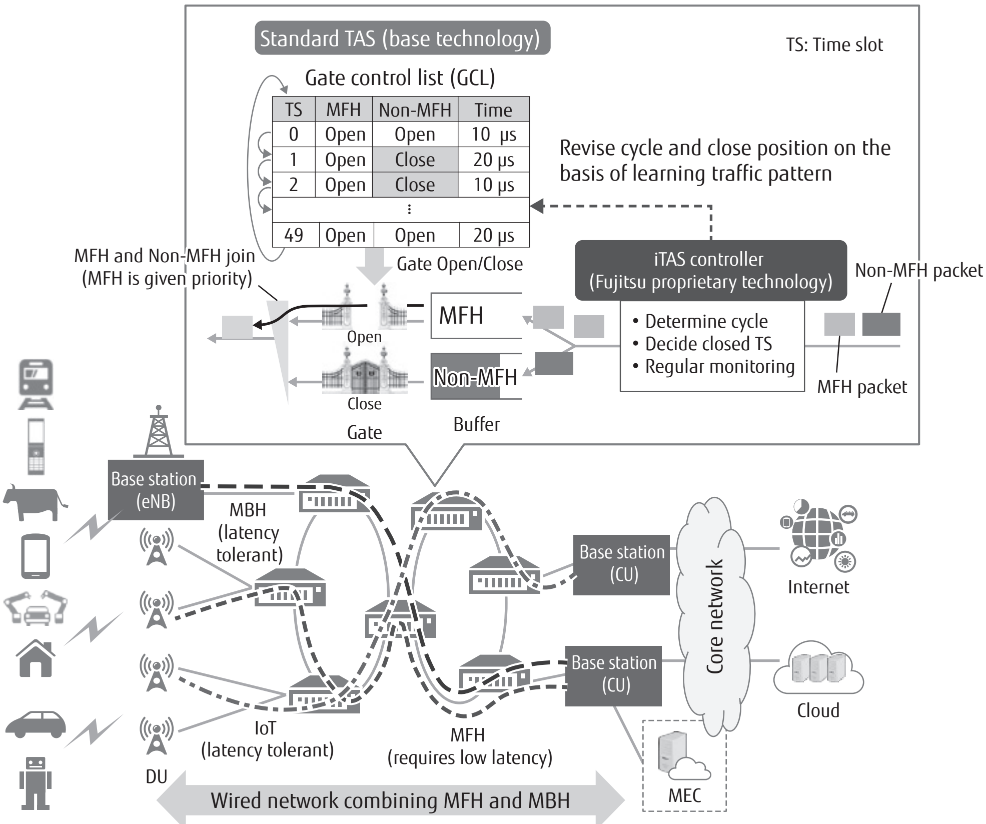
Fujitsu is studying the evolution of access networks to provide 5G services to integrated wired and wireless packet networks incorporating C-RANs. On such an integrated network, traffic with various characteristics and requirements will flow together on the same network. To achieve this, we are focusing on the Time-Sensitive Networking (TSN)3) standards (IEEE 802.1TSN), which can realize low latency on a packet network.

IEEE 802.1TSN is collection of standards studied by the TSN Task Group. It is aimed at achieving ultra-low latency and high availability in a wide range of fields such as synchronization, queuing, and bandwidth reservation. Within IEEE 802.1TSN, the 802.1CM (TSN for Fronthaul) is the standard that deals directly with low latency on the MFH, gathering together MFH network requirements and examining which other TSN standards to incorporate.

In this standard, latency performance of less than 100 µs is required on the MFH network. There are also standards related to queuing that have a direct effect on reducing packet switching delay, including 802.1Qbu, 802.3br (Preemption), and 802.1Qbv (TAS: Time Aware Shaper).

Preemption and TAS are both technologies for reducing latency caused by packet collisions, which cannot be avoided with earlier technologies. Since each technology has both advantages and disadvantages, they must be selected in accordance with the situation. However, simply implementing TAS functionality will not achieve reduced latency.

We provide a simple explanation for this using Figure 3. Standard TAS consists of a gate control list (GCL), which regulates gates for each class and the timing for opening and closing them. This is used to avoid packet collisions at the timing when MFH low-latency traffic (MFH) arrives by closing the gates for non-MFH packets. However, to realize this, the cycles and timing of MFH traffic sent from the CU and DU must be grasped ahead of time, and appropriate settings must be made



MEC: Mobile edge computing
MBH: Mobile back-haul

Figure 3
iTAS scheme in the 5G mobile access network.

in the GCL to open and close gates.

This must be done on all switches on all MFH routes. Furthermore, if nodes are added or removed, the timing on all nodes must be reconfigured. It is extremely difficult to configure this manually ahead of time, which has been a major issue with TAS in practice.

As such, we have devised the Intelligent TAS (iTAS) scheme for updating the GCL (Figure 3), which does not require detailed prior configuration and enables switches to learn the timing of MFH arrivals autonomously, after they begin operating.[4] The scheme operates with the following three phases.

- Observes MFH traffic arrival volumes in each time slot (TS), and uses autocorrelation to derive cycles and update the length of the GCL.
- Learns which TS within a cycle has MFH arrivals, and closes the gates for non-MFH classes during that TS.
- When errors or discrepancies during operation are detected, revises the location of TSs to be closed.

We implemented iTAS in software on a Fujitsu 1Finity S100 switch and evaluated it. Results confirmed that it was able to detect cycles and timing of MFH traffic simulated on a one-second cycle accurately, and update the GCL list appropriately. This achieved a reduction in latency from approximately 40 µs to approximately 8 µs. As mentioned earlier, latency on the MFH network must be 100 µs or less, so it would not be possible practically to build a network with single-node latency of 40 µs. By applying iTAS technology, the 100 µs latency provision can be met even through several nodes, so it should be possible to realize 5G service low-latency applications.

5. Optical network monitoring and operation-automation technology

To implement flexible optical networks that meet the requirements of diverse 5G services, we are conducting R&D on optical monitoring technology using deep neural networks (DNN),5) and technology to automate operation confined between opposing transmitters and receivers.6)

An overview of the optical monitoring scheme being developed using a DNN for the data processing module and a digital coherent receiver for the data metrics module is shown in **Figure 4(a)**. With this scheme, a large amount of data, including all physical quantities within the received optical bandwidth, is obtained by the digital coherent technology and learned by the DNN, which then infers transmission quality parameters. By using a DNN in the data processing component, the signal processing component can be configured automatically from the input data rather than having to monitor the state of the optical network transmission paths and optical transceiver characteristics beforehand.

We conducted tests on the proposed monitoring technology using DNN. We used optical signal-to-noise ratio (OSNR), which is a basic index of the state of the transmission path, as the parameter to be estimated. We first generated a 16 Gbaud dual-polarization quadrature phase-shift keying (DP-QPSK) signal. We varied the OSNR from 10 dB to 28 dB by adding amplified spontaneous emission (ASE) noise. Then, after coherent detection, the signal was converted from analog to digital at 40 Gsample/s without synchronizing the clock to the signal. In this way, we generated a total of 500,000 data points for DNN training. The DNN architecture implemented for these tests was a convolutional neural network (CNN) consisting of three convolutional layers, two pooling layers, and two fully connected layers.7)

The OSNR estimation results are shown in **Figure 4(b)**. The horizontal axis shows the OSNR values measured using a spectral analyzer, and the vertical axis shows OSNR values estimated using our monitor. The circles indicate training data used for fitting, while the diamond shapes indicate test data not used for fitting. These results show that accurate OSNR estimation was achieved while avoiding over-fitting. Introducing this monitoring technology into optical networks will enable the provision of services such as identifying the causes of signal degradation and recommending optimal modulation schemes. This will contribute to realizing highly reliable, efficient, and flexible optical networks.

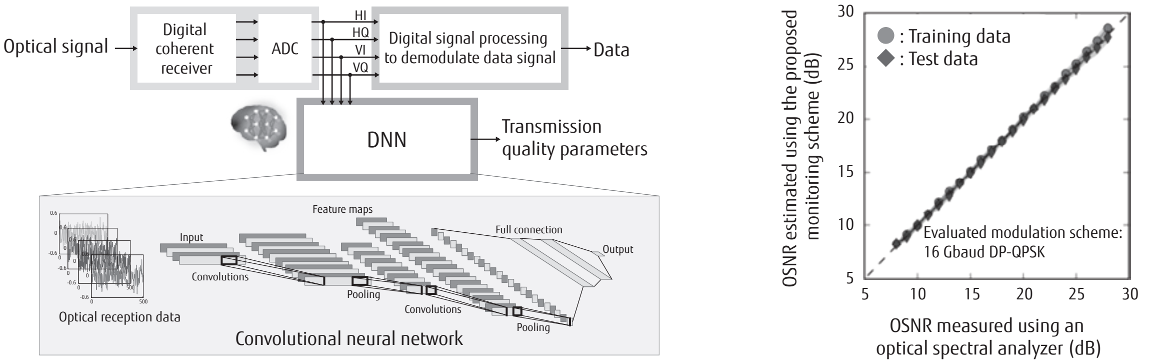
Figure 4(c) gives an overview of the automated control architecture that we have been developing. A strength of this architecture, which consists of two technologies as follows is that it performs automated control confined between opposing transmitters and receivers. The first technology is a technology that multiplexes the frequencies of control signals for direct exchanging between the opposing transmitters and receivers. The second is an optical monitoring technology that monitors signal quality, detects changes and anomalies in optical network state, and triggers control measures.

By adopting this architecture, a communicating transmitter and receiver can be notified through the monitoring and control channel of quality degradation or predictors of degradation detected by the optical network monitor. Optical network operation can then by controlled automatically by operation of communicating devices on the basis of notifications from this monitoring information.

To verify the effectiveness of this architecture, we implemented a prototype automatic configuration error detection function for configuration parameters in a commercial optical transceiver.8) As a use case, we assumed a situation in which parameters were set incorrectly between communication transceivers when they were installed in a telecommunications facility. This function automatically checked configuration values on communicating transceivers and detected the incorrectly set parameters.

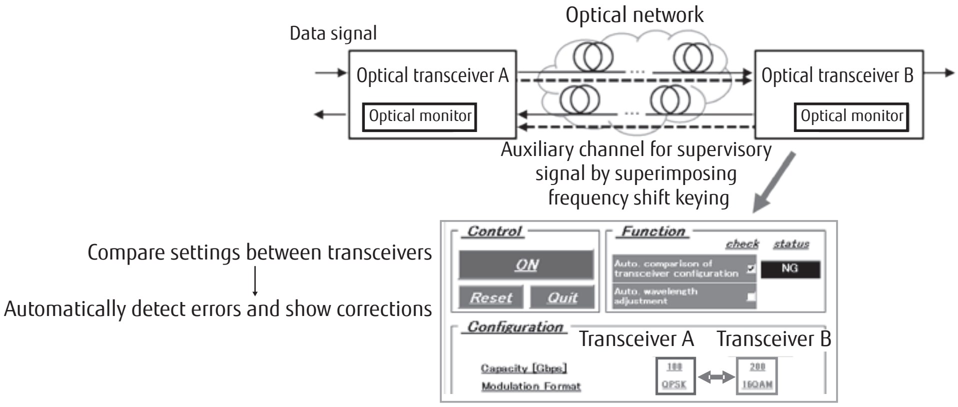
In this case, optical transceivers A and B were configured for 100 Gbaud DP-QPSK and 200 Gbaud DP-16QAM signals respectively, taken as an example. Without this function, the data signal is not transmitted because the optical transceivers are set with different modulation schemes. Conversely, with this function, the incorrect configuration between the two is detected and the result is displayed in the GUI, as shown in Figure 4(c). This demonstration confirms that the proposed automatic control architecture is effective for automating operation of optical networks.

In the future, the DNN optical monitoring technology described above will be used to advance technology to monitor for various types of degradation in signal quality without changing hardware and to advance automation of optical network operations on the



(a) Overview of Deep Learning technology for monitoring the optical physical layer

(b) Estimated OSNR value for a 16 Gbaud DP-QPSK signal



Prototype GUI example

(c) Architecture for automatic control confined between opposing transceivers.

Figure 4
Overview of technologies for optical monitoring and automation of optical network operation.

basis of monitoring data.

6. Conclusion

This paper discussed various challenges with optical networks providing social infrastructure and supporting 5G services that will be launched in 2020. Furthermore, it introduced various initiatives at Fujitsu to address these challenges.

Fujitsu will continue to advance R&D toward implementing products with these technologies and contributing to the deployment of 5G services.

This paper contains a part of the results from R&D projects under contract with the Ministry of Internal Affairs and Communication, titled "The Research and Development Project for the Ultra-high Speed and Green Photonic Networks." It also contains a part of the results from R&D projects for radio resource enhancement under contract with the Ministry of Internal Affairs and Communication, titled "Wired-and-Wireless Converged Radio Access Network for Massive IoT Traffic." It also contains results of research that the Photonics Electronics Technology Research Association (PETRA) contracted from the New Energy and Industrial Technology Development Organization (NEDO), titled "Photonics Electronics Convergence Technology for Power-Reducing Jisso System."

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