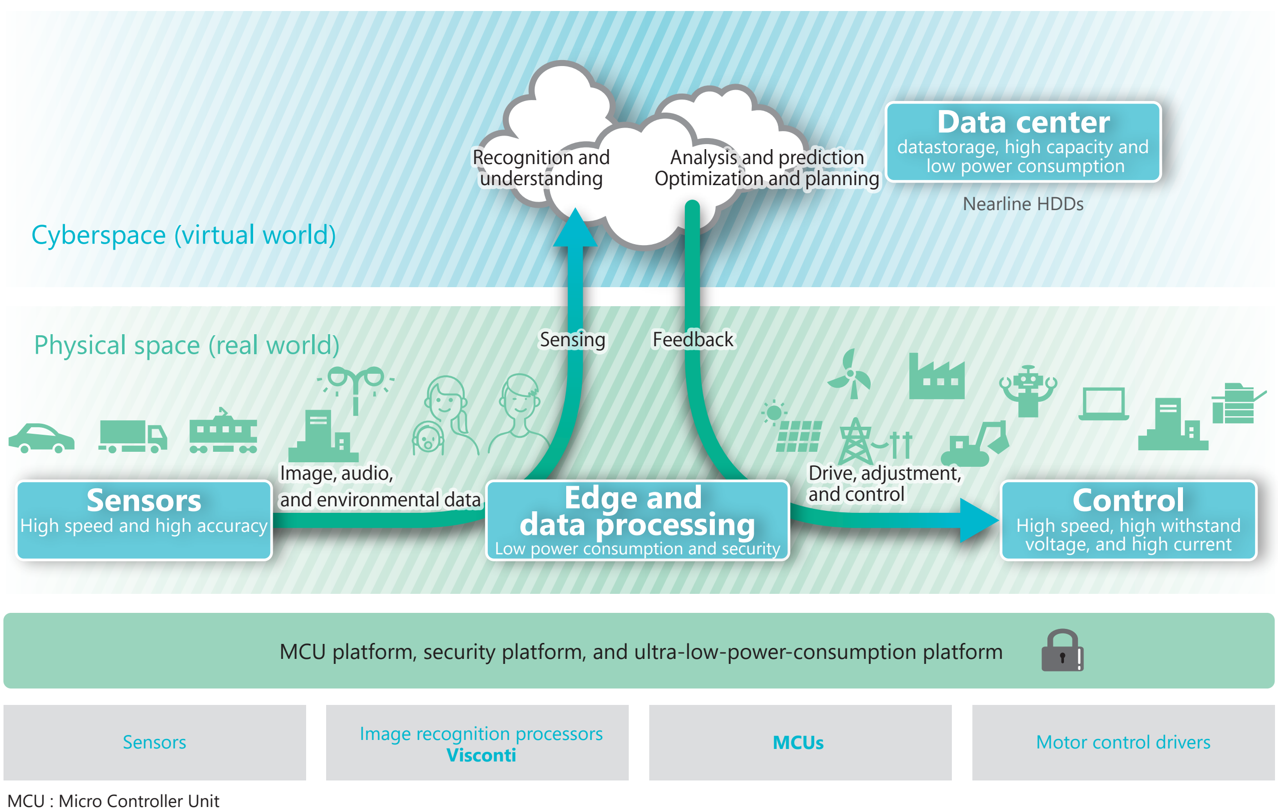
Toshiba Group's Approach to Storage and Semiconductor Technologies for Cyber-Physical Systems

The increasing volume of data being generated accompanying the worldwide expansion of the Internet of Things (IoT) and artificial intelligence (AI) has given rise to the need for the development of systems and services to economically and efficiently collect and store these data in order to make effective use of them. Electronic components including storage devices and semiconductor products related to data are also expected to play a critical role in the evolution of technologies and functions essential in the expanding field of cyber-physical systems (CPS) in the future.

The Toshiba Group is offering various solutions in both the cyber and physical spaces aimed at expanding the CPS businesses through the development of hard disk drives (HDDs) that can hold large volumes of valuable data, as well as semiconductor products that can not only process these data but also control edge devices based on the processing results.



Overview: HDD and semiconductor products to attain functions required for CPS

1. Introduction

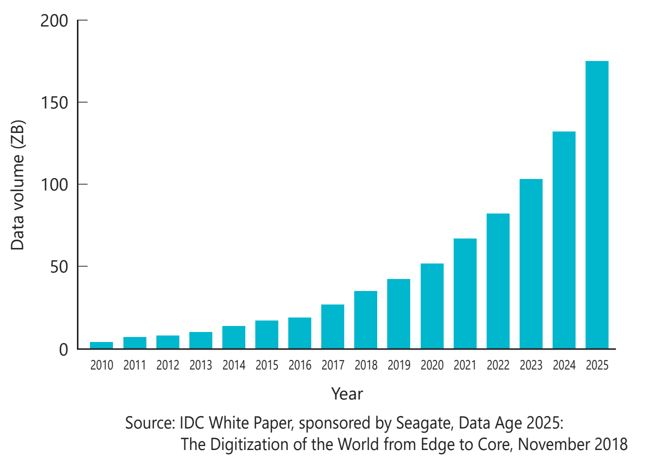
To date, we have witnessed many accomplishments in the field of information and communication technologies (ICTs), including the invention of deep learning (i.e., methods of increasing the depth of neural networks) in the late 2000s; the ever-increasing performance of central processing units (CPUs) and graphics processing units (GPUs); and the expansion of data centers that collect data for deep learning. These accomplishments have spawned new technologies and businesses based on big-data analytics. Nowadays, the term "artificial intelligence (AI)" is used in everyday language.

In addition, as typified by the Internet of Things (IoT), the progress of wireless communication networks has made it possible to connect numerous devices around the world to the Internet, leading to the introduction of various services, including data communication and remote system operation. As the IoT and AI become more prevalent, the amount of data generated worldwide is increasing at an explosive rate and is forecast to reach 175 zettabytes (ZB; 1 ZB = 10^{21} bytes) in 2025 as shown in **Figure 1**[(1)]. Under these circumstances, it will become increasingly important to economically and efficiently collect and store these data while extracting and utilizing useful data swiftly.

The amount of data used for big-data analytics is also growing every year. The ever-increasing communication traffic over the Internet is becoming a bottleneck for data collection and edge services. Therefore, edge computing, a distributed computing paradigm that brings data processing closer to edge and endpoint devices, is becoming more important than ever before. In addition, fog computing is attracting a lot of attention as a means of optimizing the operation of data storage, analysis, and control services between edge devices and data centers.

Most of the extensive data sensing, computing, communication, and control functions that characterize CPS are implemented by a combination of semiconductor devices and embedded software. Furthermore, the security technology necessary to ensure the reliability of CPS is expected to be incorporated into semiconductor devices. Therefore, CPS will require high-capacity data storage devices and semiconductor devices for the implementation of their functions. In CPS, cloud computing in cyberspace is deeply intertwined with endpoint devices and various edge solutions in physical space. Toshiba Electronic Devices & Storage Corporation leverages CPS to contribute to the development of a new society where big data and AI will drive ICTs (**see Overview diagram**).

This report discusses technical trends concerning nearline HDDs that will become major storage devices in data centers as well as semiconductor devices related to CPS.



* Created based on "The Digitization of the World - From Edge to Core"[(1)] by Reinsel, D. et al.

Figure 1. Trends in total volume of data generated worldwide
With the prevalence of big data, IoT, and AI, the amount of data generated worldwide is growing at an explosive rate and is expected to reach 175 ZB in 2025.

2. Technical trend for nearline HDDs

2.1 Market trend for nearline HDDs

The word "nearline" stands for "near-online," a new category that stands between high-performance online storage required for high-speed data processing and offline storage that prioritizes long-term data storage.

To achieve high performance, conventional online data storage has relied on 2.5-inch HDDs with a rotation speed of

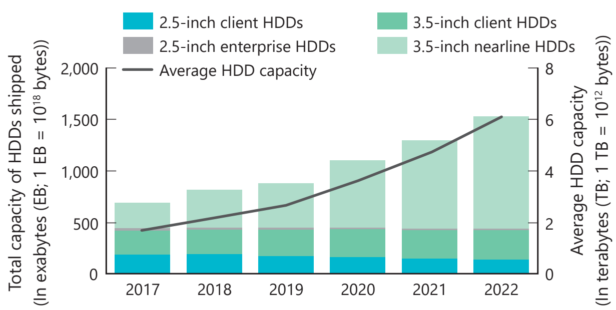
10,000 or 15,000 revolutions per minute (rpm). In the 2000s, solid-state drives (SSDs) also appeared as an alternative online data storage. Magnetic tape has been used for offline data storage.

To attain even higher data processing speed, high-performance SSDs are becoming widely used as online storage, but their per-bit cost is still much higher than that of HDDs.

As described above, the data centers that provide cloud services must retain data online to allow the use of the rapidly increasing amount of data. Enormous investment and operating costs are required for such data storage. As an optimum solution for the reduction of the total cost of ownership (TCO), the market demand for 3.5-inch 7,200-rpm nearline HDDs is increasing, particularly for data centers and other mission-critical facilities[*1].

Although the prices of SSDs are decreasing, it is forecast that they will continue to remain more expensive than nearline HDDs. Therefore, the applications of SSDs and nearline HDDs are becoming increasingly differentiated particularly in data centers, where SSDs are employed as online storage to process data at high speed while nearline HDDs are used to store the increasing amount of data.

The market for nearline HDDs will continue to expand because of an explosive increase in the demand for data storage. In terms of total capacity, the shipment of nearline HDDs is forecast to increase at an annual rate of roughly 35% as shown in **Figure 2** because of their advantage in terms of the TCO.



* As of July 2019 (as surveyed by Toshiba Electronic Devices & Storage Corporation)

Figure 2. Trends in total capacity of HDDs shipped

In terms of total capacity, the shipment of nearline HDDs is forecast to increase at an annual rate of roughly 35%.

(*1) Total cost, including the initial investment cost (i.e., the cost of acquisition) and the operating costs (i.e., the costs of maintenance and operation) of computer systems

2.2 Specifications required for nearline HDDs

Data centers are making huge investments in storage devices, which will continue to increase in the years ahead. To help reduce the TCO of an overall storage system, it is important to (1) reduce the per-bit cost, (2) increase the storage capacity, and (3) reduce the power consumption of nearline HDDs.

Each successive generation of nearline HDDs provides higher per-platter capacity due to an increase in recording density and higher HDD capacity due to an increase in the number of platters within an HDD. However, there is a trade-off between the capacity and power consumption of an HDD. The helium-sealed HDD was invented to solve this problem.

2.3 Helium-sealed HDDs

Being smaller in molecular weight than the air, the helium molecule causes less buffeting, reducing the vibration of head suspension assemblies and the fluttering of disk platters at high rotation speed. This, in turn, helps to improve the positioning precision of the actuator arms and therefore increase the recording density of HDDs.

In HDD manufacturing, the servo information necessary for the head positioning is written on data storage media. Helium had long been used for this process to achieve high-precision positioning. It was difficult, however, to ensure complete hermetic sealing of helium gas in the conventional HDD enclosure for the lifetime of the HDD's operation. To overcome this problem, a new sealing technology was necessary.

To realize helium-sealed HDDs, we achieved high hermeticity by using precision laser welding technology to weld the top cover of the HDD enclosure.

Helium has less drag force acting on the spinning platters than the air, making it possible to reduce the power consumption of the spindle motor. In addition, when the number of platters is increased, helium causes a substantially less increase in power consumption than the air. Therefore, helium-sealing technology makes it possible to squeeze a greater number of platters inside the HDD enclosure without causing an increase in power consumption.

By leveraging these characteristics, we released the MG07 series of 14 terabyte (TB; 1 TB = 10^{12} bytes) HDDs in 2017 that contain nine platters in a 3.5-inch enclosure with a height of 26.1 mm[2]. The MG07 series provides 40% higher capacity, but consumes roughly 42% less power, than the previous 10 TB MG06 series, greatly contributing to a reduction in the customer's TCO.

With the advent of helium-sealed HDDs, the market of nearline HDDs was divided into two segments: conventional nearline HDDs with a capacity of 8 TB or less for on-premises storage and helium-sealed HDDs with a capacity of 10 TB or more primarily for use in data centers. Demand for helium-sealed HDDs is expected to continue growing mainly for data center applications while demand for conventional nearline HDDs with a capacity of 8 TB or less will maintain the current volume.

We will continue to release high-capacity nearline HDDs incorporating new magnetic recording, data processing, and other technologies.

2.4 Helium-sealed HDDs

HDDs are a collection of various cutting-edge technologies, including magnetic recording, signal processing, servo control, mechanical structural analysis, fluid dynamics, and tribology. HDDs have evolved with the advancement of these underlying technologies. In 2005, we achieved practical use of perpendicular magnetic recording (PMR), a technology for data recording on magnetic media that arranges magnetized cells in the perpendicular direction instead of the conventional longitudinal direction. The PMR technology overcame the problems of demagnetizing field and thermal instability between magnetic particles that occurred in high-density longitudinal recording media, contributing to a recent increase in recording density.

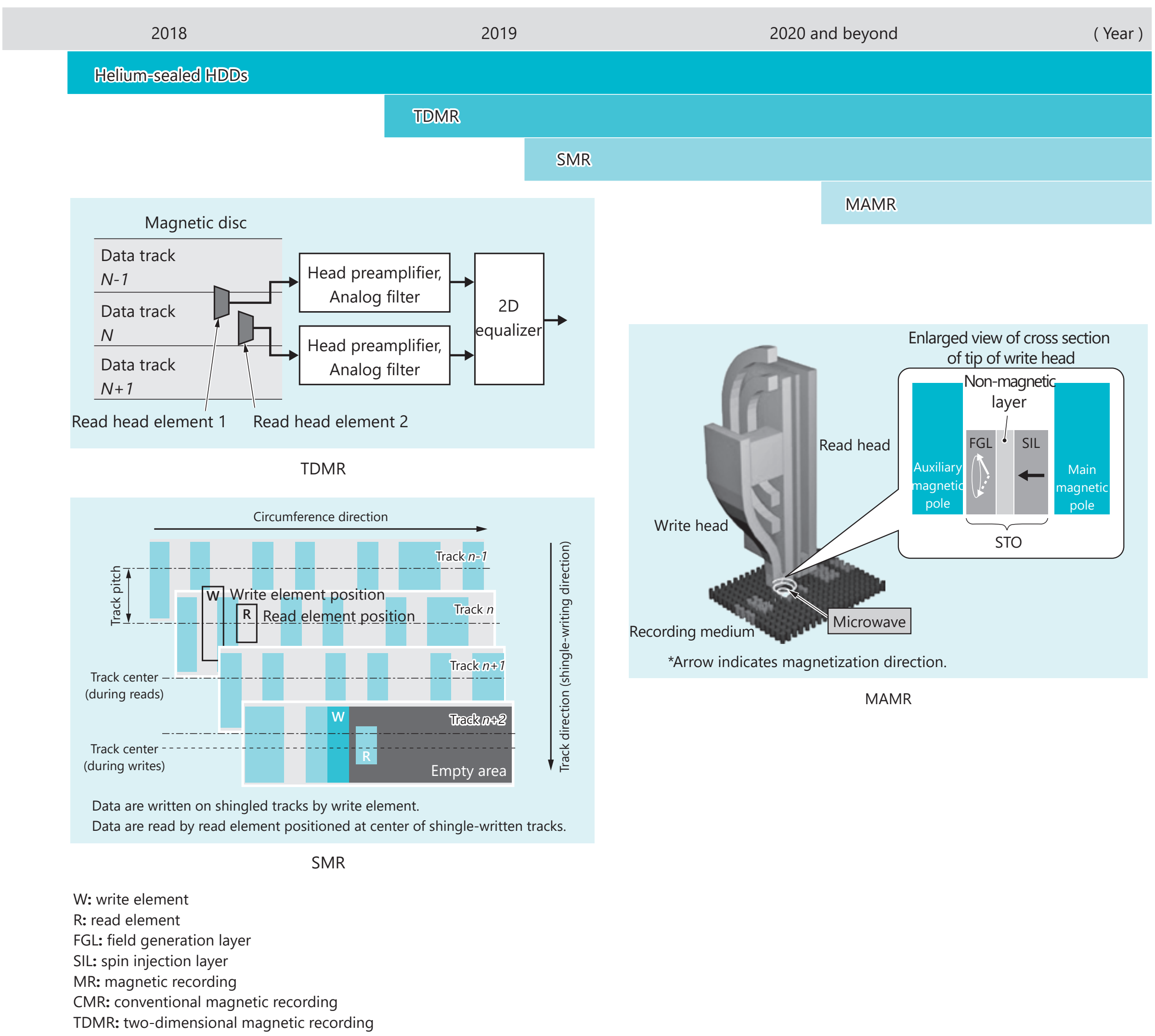


Figure 3. Roadmap for large-capacity HDD technologies
To combine high writability, signal-to-noise ratio, and thermal stability, we will promote the development of various innovative technologies to provide cutting-edge nearline HDDs.

At present, perpendicular magnetic recording is facing a trilemma of (1) data writability, (2) signal-to-noise ratio (SNR), and (3) thermal stability. The maximum recording density achievable with perpendicular magnetic recording is considered to be roughly 1 Tbit/in^2 (one terabit per square inch)[(3)].

We are planning to develop various new technologies to solve this trilemma so as to commercialize nearline HDDs as shown in **Figure 3**.

Shingled magnetic recording (SMR) is one of these technologies. SMR is a technology to achieve a high recording density by writing a new track, overlapping part of the previously written track in a manner akin to roof shingles. Although SMR is already widely used for client HDDs targeting a wide range of markets, SMR HDDs cause a longer write latency than conventional HDDs unless the host system optimizes data write operations specifically for SMR. The International Committee for Information Technology Standards (INCITS) has standardized a new command set for SMR HDDs for data centers and other server storage applications that prioritize data write latency. In line with this, technological development is currently underway in the HDD industry to make the best use of SMR HDDs with a host system. We are also developing high-capacity nearline HDDs incorporating SMR technology.

In addition, we are working on the development of microwave-assisted magnetic recording (MAMR) technology, a next-generation magnetic recording technology for 2020 and beyond to improve the writability and thereby increase the recording density of magnetic media. For this purpose, MAMR uses a spin torque oscillator (STO) to generate and add a microwave field to the recording magnetic field.

As described above, we will continue to commercialize cutting-edge nearline HDDs, leveraging new innovative technologies.

3. Semiconductor devices supporting CPS

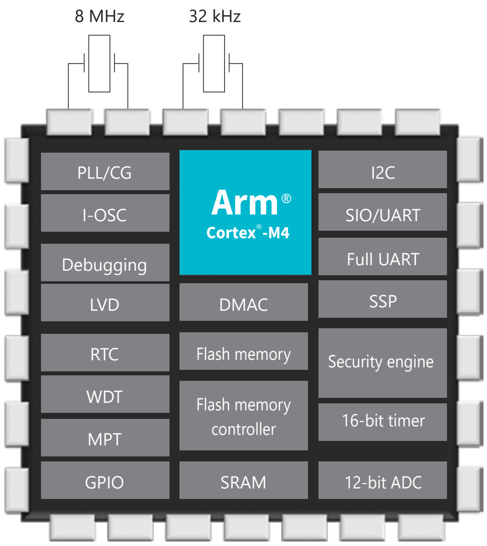
As described in Section 1, many kinds of semiconductor devices are necessary to attain the functions of a large architecture that consists of a mixture of layered technologies, ranging from sensors for CPS to cloud computing. Although performance and other specification requirements differ layer by layer, the component functions in all layers can be categorized into computing, communication, data storage, control, security, etc. In particular, there are many pioneering requirements for microcontroller units (MCUs) for endpoint devices that process sensor signals. To satisfy these market requirements, we provide the TMPM46BF10FG MCU incorporating security functions. **Figure 4** shows a typical block diagram of an MCU for endpoint applications and typical technical requirements. As a differentiating technology for the MCU hardware, we have also developed a secure firmware rotation technique that makes it possible to safely update firmware even in the event of a system software vulnerability being attacked.

In addition, the endpoints of CPS need semiconductor solutions that anticipate future implementation of more than a trillion sensors. To ensure the security of countless endpoints, it is necessary to provide practical solutions to improve the efficiency and enhance the robustness of individual endpoint devices. For this purpose, we have concluded a business alliance on trust services for IoT devices with Cybertrust Japan Co., Ltd. that has a proven track record in digital authentication. Our expertise for the design and implementation of devices will be combined with the embedded Linux, authentication, and security technologies of Cybertrust to architect systems that protect the confidentiality, integrity, and availability of IoT devices throughout their life cycle from design to disposal.

Specifically, this alliance will conduct market research, promote joint sales activities, and consider the requirements for constituent technologies regarding the solutions that combine our MCU and Cybertrust's secure IoT platform. Cybertrust will develop and provide trust services for IoT devices, including device provisioning using device certificates, device authentication services, and a mechanism for firmware updating, based on its expertise and experience in authentication and security services as well as Linux services for embedded devices[(4)]. We are aiming to commercialize MCUs ready for these services in 2020.

Another basic characteristic of CPS is the use of actuators to control physical devices. We have decades of experience in the development of semiconductor devices for motor control applications. To optimize motor control for CPS solutions, it is necessary to integrate advanced algorithms, MCU technologies, and electric power control. In the field of server cooling fans, we have commercialized the TC78B025FTG motor driver IC that is designed to reduce power consumption by fine-tuning the phase of the motor drive voltage, decrease motor vibration through sine-wave commutation, and achieve stable rotation speed regardless of a motor's load condition.

Figure 5 illustrates the application of motor control drivers (MCDs) and MCUs that will become increasingly important with the prevalence of CPS.



Typical technical requirements

- Low power consumption and high performance are emphasized.
- Security engine is incorporated.
- Computing performance and embedded memory capacity are optimized.
- External interfaces required by IoT endpoints are incorporated.

PLL/CG **:** phase-locked loop/clock generator
I-OSC **:** internal oscillator
LVD **:** low-voltage detect
RTC **:** real-time clock
WDT **:** watchdog timer
MPT **:** multi-purpose timer
GPIO **:** General Purpose Input/Output
DMAC **:** direct memory access controller
SRAM **:** Static RAM
I2C **:** Inter-Integrated Circuit
SIO/UART **:** Serial Input Output/Universal Asynchronous Receiver Transmitter
SSP **:** Synchronous Serial Port
ADC **:** analog-digital converter

Figure 4. Typical block diagram of MCU for CPS endpoint devices
MCUs need to provide various, but just enough, functions for endpoint devices, including computing units, input/output (I/O) interfaces, embedded memory, and a security engine.

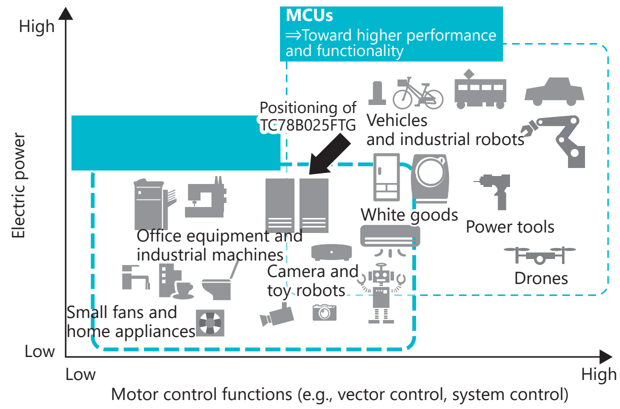


Figure 5. Application of motor control semiconductors for CPS
Different applications require different functions, ranging from simple motor rotation control to complicated vector control. The required output current also depends on the application. MCDs are suitable for relatively simple motor control requiring low output current while motor control solutions using an MCU provide high performance and functionality.

4. Future outlook

High-capacity data storage and semiconductor devices play critical roles in realizing the functions necessary for CPS, including extensive data sensing, computing, communication, and control.

The deployment and application of CPS will continue to increase. We will provide various solutions using new technologies to contribute to the development of CPS.

References

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(2) Toshiba Electronic Devices & Storage Corporation. 2019. “Toshiba Electronic Devices & Storage Corporation Launches World’s First 14TB HDD with Conventional Magnetic Recording.” News release / Products / Public Information. Accessed July 12, 2019. https://toshiba.semicon-storage.com/ap-en/company/news/news-topics/2017/12/storage-20171208-1.html.

(3) Yamamoto, K. 2012. “Technology Trend and Market Expansion of Hard Disk Drive.” The Journal of the Institute of Electrical Engineers of Japan. 132 (2): 97-100.

(4) Toshiba Electronic Devices & Storage Corporation, Cybertrust Japan Co., Ltd. 2019. “Toshiba Electronic Devices & Storage Corporation and Cybertrust Japan Co., Ltd. Conclude a Deal on Trust Services for IoT Equipment (in Japanese).” News release / Products / Public Information. Accessed July 12, 2019. https://toshiba.semicon-storage.com/jp/company/news/news-topics/2019/07/micro-20190709-1.html.