Disaggregated Computing Access Network using Newly Structured Hollow-Core fiber for AIoT Platform (Invited Talk)

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***Abstract*—The Artificial Intelligence (AI) platform is needed to control the dynamic Internet of Things (IoT)-network with many IoT devices, such as self-driving vehicles, robots, etc., whose movements are changing. We describe the architecture of an access network that should serve as an AI platform for this purpose, connecting an area of about 10 km with low latency and tightly integrating edge computers, etc. We propose a time-space-synchronous digital twin, part of which is being developed as a proof of concept (PoC). For AI applications, information from sensors and other IoT devices will be sent to the network (digital twin) in real time, where AI processing will be performed by linking edge devices and the center cloud. For this purpose, we have created an IoT Box for AI that can be powered from the network, and can link AI networks with low power consumption.**

For this comprehensive research, Keio University created the "Keio Future Optical Network Open Research Center" with the support of the Ministry of Internal Affairs and Communications (MIC), and began research on a testbed.

Keywords*— *Beyond 5G, Low latency, Hollow-core fiber, Optical Network, IOWN, Digital Twin

I. INTRODUCTION

In the 21st century, optical networks have made great progress as a high-speed, wide-band link technology, and computer science services such as cloud services have been enriched. In the next generation Beyond 5G (B5G), further development is being encouraged in seven areas in particular [1, 2], among which ultra-low latency and energy saving are given high priority. Ultra-low latency services are in high demand for new smart social services such as robot control and autonomous driving. In addition, low latency is important not only in the conventional wireless access section but also in a certain range (we call it “area space” which is approximately 10 to 20 km area). On the other hand, low power consumption is also a goal of the sustainable development goals (SDGs), and there are high expectations for optical technology, which can achieve power savings of 1/500 to 1/1,000 compared to electricity. This article describes in detail the status and goals of the research conducted by Keio University's “Keio Future Optical Network Open Research Center” which has been underway since 2023 [3].

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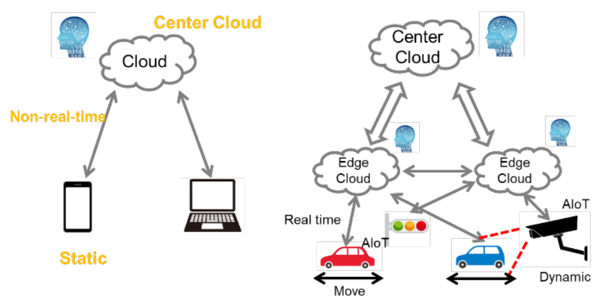
II. DYNAMIC AIOT (AI EMPOWERERD IOT) PLATFORM

Artificial Intelligence (AI) has made remarkable progress and is extremely powerful both as a smartphone and as a personal computer (PC) service. Fig. 1 outlines the current platform and the configuration of future, more dynamic platforms for AI empowered Internet of Things (IoT).



(a) (b)

Fig. 1. Dynamic AIoT Platform. (a) Conventional static platform. (b) Dynimic, Distributed AI empowered IoT (AIoT) Platform.

Fig. 1(a) shows the AI platform in its current configuration with a large number of training data collected in a huge center cloud. It is possible to collect a lot of training data, and much of it is due to static processing. On the other hand, when considering the control of objects that involve many devices moving further, for example, autonomous-driving vehicles (ADVs), it is necessary to prevent collisions, and traffic signal control, etc., as opposed to simple mixed expectations. The configuration is shown in Fig. 1(b). Many distributed AI empowered IoTs (AIoTs) are dynamically connected and interacted each other.

We consider several new requirements for dynamic AI process. (1) There are many AIoT devices to be controlled. (2) Each AIoT device is moving. (3) Real-time control is required. In addition, we need (4) energy reduction in relation to (1). We have started to study the architecture of a network that

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addresses (1) to (4). We describe our evaluation of each technology in Table 1.

In this paper, we describe the technologies aiming at a time-space synchronous digital twin in response to (2) and (3). A time-space synchronous digital twin is a real-time communication between IoT and edge networks by minimizing latency to the limit. In addition, in a certain area (e.g., 10 to 20 km), edge computers are tightly coupled with low latency to share resources through dis-aggregated computing. In other words, the entire area is intended to become and operate as a single computer. In this paper, we describe the applications that the time-space synchronous digital twin will create along with the technologies to realize them.

TABLE I. AI + IoT NETWORK REQUIREMENTS

#	Requirement	Key techniques
(1)	Massive IoT Device	Distributed / Edge Control
(2)	Dynamic IoT Control	Edge Cloud / Center Cloud Cooperation Disaggregated Computing
(3)	Real Time Control	Super Real Time Communication Disaggregated Computing
(4)	Energy Consumption	Energy Harvesting Automatic Sleep Control Edge-IoT Cooperation

III. ULTRA LOW-LATENCY NETWORK TECHNOLOGY CALLED "TIME-SPACE SYNCHRONIZED DIGITAL TWIN"

A. *Area space computing and time-space synchronization digital twin*

The key-component to realize time-space synchronization is a low latency provided by the new-type of optical fiber "Hollow-core fiber (HCF)". The structure, principle, and merits of HCF will be discussed latter. We have installed the HCF in the campus [3, 4] to create an extremely low-latency network in a certain area (~20 km) and to synchronize computer and memory resources. This is an application of the development of technology that allows low-latency fixed connections. Fig. 2 shows B5G, which is the aim of this research. In this way, we aim to achieve low latency between or among systems, rather than low latency at points like conventional 5G wireless access. Resources within a certain area are treated as a tightly coupled resource pool without being aware of their location. Therefore, efficiency is high and energy can be reduced. Because unused systems can be power down and performance scale-out or scale-down can be automatically done.

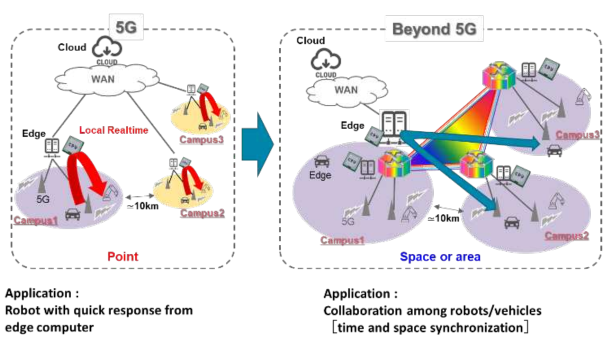

Fig. 2. Area space computing having time-space synchronization

Fig. 3 shows the spatiotemporal synchronized digital twin that they are aiming for. Synchronize and acquire information between devices dispersed in space for example, ADVs and create a digital twin on cyber. According to Fig. 4, based on the information on the network, predict the short-term future for example, 30 seconds later in an intersection. If ADVs collide at a planned future intersection, there is time to simulate whether or not to let one of them go first. This is called a "future-predicting" or "future-ideal" digital twin. We aim to create something that can backwards control the present to create the safest and most efficient future in terms of energy.

This is the vision of the Keio Future Optical Network Open Research Center. In this way, we will consider everything from devices to network technology that makes full use of them, and even computer architecture, and will also collaborate with research on applications such as autonomous driving and real-time control robots. For this reason, Keio University has established an open research center and is recruiting collaborators from basic research stage.

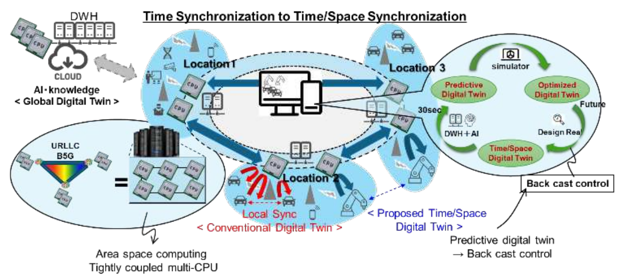

Fig. 3. By time-space spatiotemporal synchronization, idea and predictive digital twin.

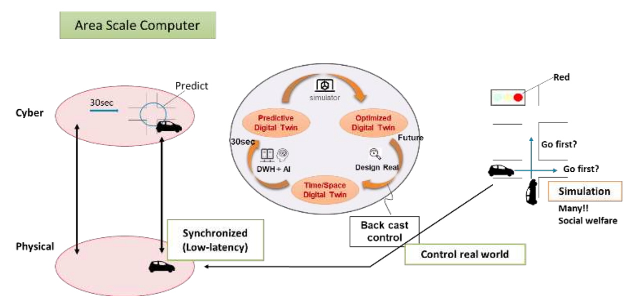

Fig. 4. Time & space synchronized digital twin computing

B. *Super multi-brach access network for AIoT platform*

The MIC's Research and Development of Advanced Optical Transmission Technology Contributing to a Green Society (JPMI00316) (research representative: Oki Electric Industry) [5] is proceeding with research and development using the network architecture shown in Fig. 5.

This is an economical ultra-high-speed passive optical network (PON) technology in the 400 Gbps class for distributed cloud access and a super multi-branch PON technology that covers IoT and sensors [6]. Current PON mainly covers residential use, and it is said that reliability and bandwidth are still insufficient for mobile backhaul, cloud red and edge computing. On the other hand, devices such as IoT and sensors that use almost no bandwidth, and devices such as sensor cameras that are only used when someone is present and are turned off the rest, have also entered subscriber

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networks. Taking these into account, B5G is also considering super multi-branch access for economical solution.

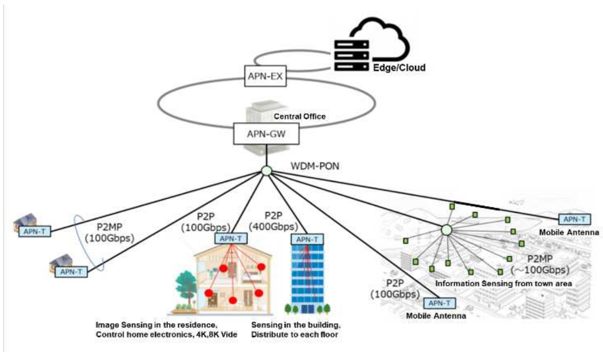


Fig. 5. Next generation access network architecture by JMPI00316 project.

C. *Newly structured Hollow-Core fiber*

Fig. 6 shows the structures of an ordinary single-mode fiber (SMF) and an HCF. Fig. 7 shows a cross-sectional photograph of the HCF [7, 8]. There is another structure called anti-resonant type HCF [9,10] but because of better performance for real use, we use the photonic band gap type hollow core fiber (PBGF-HCF). HCFs have a crystal structure in their cladding, and the diameter of the core portion, where light is successfully confined in the air portion of the core through Bragg reflection, is larger than that of ordinary SMFs. Since the core is air and refractive index of air is very small (n=1.0003), the following three major characteristics are expected. Table 2 shows three features of an HCF.

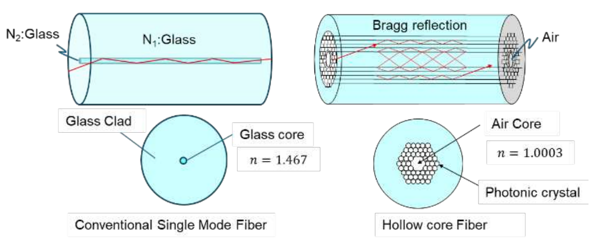


Fig. 6. Image of optical transmission using SMF and HCF.

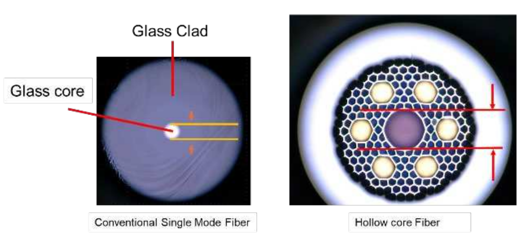
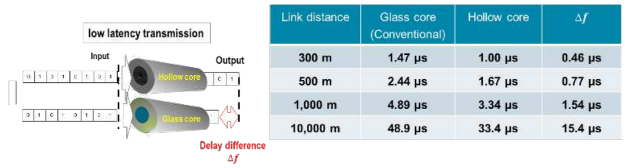


Fig. 7. Cross-section view of SMF and HCF (Image: size adjusted).

(1) High-power optical signals can be transmitted. This is because most of the power is confined in a hollow-core (air-core), and the damage threshold of the HCF is about 1,000 times higher than that of the conventional one [11]. This makes power over fiber (PWoF) applications, where energy is distributed by high power light, highly feasible. In addition, the number of wavelength multiplexes can be greatly increased, improving the feasibility of ultra-multi-wavelength networks.

(2) The second advantage is ultra-low latency. The speed of the signal propagation in an optical fiber is the speed of light (3 x 10^8 m/s) divided by the refractive index of the core [12-14]. This reduces latency, which will be the most important factor for networks in the future, can be reduced to about 2/3. Fig. 8 shows an image of this.



Link distance	Glass core (Conventional)	Hollow core	Δf
300 m	1.47 μs	1.00 μs	0.46 μs
500 m	2.44 μs	1.67 μs	0.77 μs
1,000 m	4.89 μs	3.34 μs	1.54 μs
10,000 m	48.9 μs	33.4 μs	15.4 μs

Fig. 8. Low latency transmission for newly structured fiber

(3) Finally, the HCF has high linearity. Optical fibers have a non-linear effect such as self- phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), Brillouin scattering, Raman scattering, and so on. When high energy light is injected into the conventional fiber, the transmission signals are severely degraded by the non-linear effects [15,16]. In addition, signals requiring high linearity, such as analog signals, were not suitable for transmission over conventional fiber. This problem may be solved by using an HCF [15,17,18].

TABLE II. CHARACTERISTICS OF HCF

#	Characteristics	
	Feature	***Explanation***
(1)	High eneryg transmission	≈ 1,000 times large than SMF ∵ Air core
(2)	Ultra low latency	$v = \frac{c}{n}$, c : 3×10^8 m/s, n: refractive index of medium SMF: n = 1.4 HCF: n = 1.0003
(3)	High linearity	Air Core → Radio on Fiber (RoF)

This paper will mainly discuss IoT devices for AI, using features (1) and (2).

IV. IOT FOR AI NETWORK

A. *AIoT box for AI application*

The IoT is characterized by a large number of devices, with diverse performance requirements and functions. As they are user devices, they must be cost-effective and at the same time consume less battery power and electricity. Therefore, the following four points were considered for the IoT platform for AI.

(1) It can be connected with ultra-low latency / high bandwidth.
(2) Supplying energy from the network.
(3) Automatic sleep, etc., for low power consumption.
(4) Have a small embedded central processing unit (CPU) that can work with the CPU (cloud) in the network.

For ultra-low latency and energy supply to the IoT, we are challenging the PWoF technology with HCFs. Fig. 9 shows the configuration of an IoT box for AI (AIoT Box); since AI

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links numerous IoT sensors to collect learning data, etc., this platform is as low power as possible.

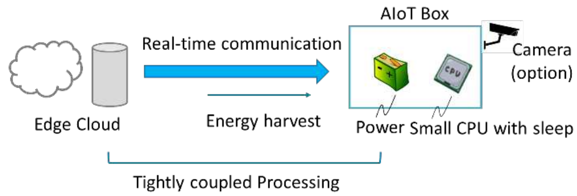


Fig. 9. AIoT Box concept.

B. Power of Fiber (PWoF) technology

Power transmission technology using optical fibers has been pioneered by Matsuura et al.[19, 20]. Furthermore, studies have begun on optical network units (ONUs) using auto-sleep ONUs and PWoF, with introducing IoT and other services to subscribers [21, 22]. High power transmission is also demonstrated [23]. We created the world's first optical power supply module using the HCF. Fig. 10 shows its circuit block, and Fig. 11 shows its external appearance. I would like to report the details separately. And Fig. 12. is experimented setup of AIoT Box proof of concept (PoC) system. The system consists of camera, low power CPU and controller.

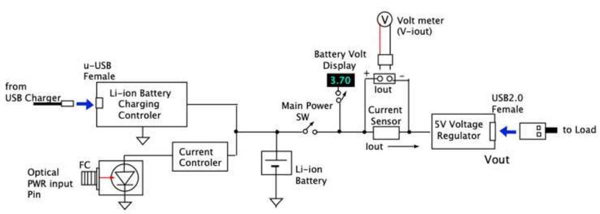


Fig. 10. Circuit diagram of PWoF power supply module.

Fig. 11. Prototype system of the PWoF power supply module.

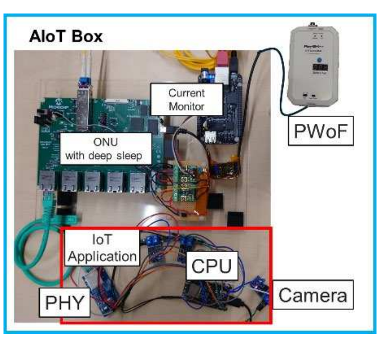
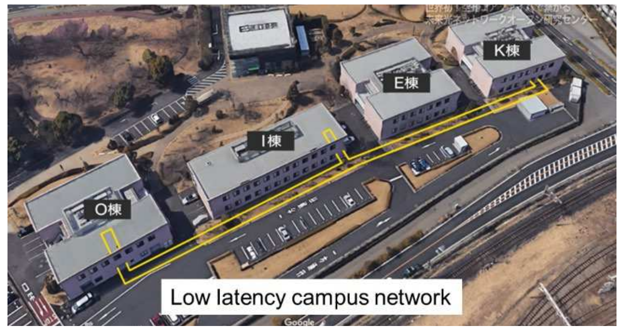


Fig. 12. Proof of Concept system of the AIoT Box.

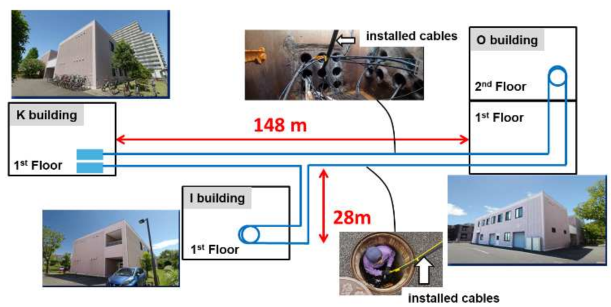
V. Ultra-low latency campus [24]

Fig. 13 shows the world's first Hollow-ocre fiber campus installation diagram [3, 4]. A newly developed cable was installed inside the manhole, making it possible to conduct research at a level close to practical use. To realize this, "Future Photonic Network Open Lab." is constructed in the Keio Furer Optical Network Open Research Center.

The "Open Lab." member including associated member is 2 service provider 6 vendors and 5 academies. The campus has real HCF network and servers, edge cloud, 5G wireless access system for infrastructure. In addition, real ADVs, real haptics robots can be used.



(a)



(b)

Fig. 13. Ultra-low latency network using HCF in the Keio Shin-Kawasaki campus. (a) Overview of the Keio Shin-Kawasaki low latency campus network. (b) Detail of the HCF cable route.

VI. Conclusions

We have proposed a time-space synchronous digital twin that tightly couples edge computers, etc. The digital twin connects an area of about 10 km with the ultimate low latency technology using HCF making a partial PoC system. AI processing is achieved by linking edge computers and the central cloud. Keio University is engaged in comprehensive research on these issues. We start Future Photonic Network Open Lab. in Keio Shin-Kawasaki campus. These technologies and PoC system can be applied for future 5G and 6G network.

Acknowledgment

This research was supported in part by the Ministry of Internal Affairs and Communications' Research and Development of Advanced Optical Transmission Technology Contributing to a Green Society (JPMI00316) and the National Institute of Information and Communications Technology (NICT) commissioned research (JPJ012368C08501). Experiments and research were conducted at the Keio University Future Optical Network Open Research Center. This new functional fiber was developed mainly by OFS and Furukawa Electric.

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