Trial of the External Electric Power Supply-Less IoT System Using Hollow Core Fiber

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***Abstract*— Wired IoT system without electrical power feeder was examined. An application-driven IoT system using a deep sleep algorithm and high-efficiency Power over Fiber (PWoF) with hollow core fiber was developed and power measurement experiments were conducted. We also verified energy harvesting with PWoF and its ability to drive an IoT system without an external power source. The developed IoT system could be driven once every 16.3 minutes without an external power source, with an average power consumption of 105 mW.**

Keywords—IoT, Passive Optical Network, Power over Fiber, Deep Sleep, Hollow Core Fiber

I. Introduction

Fiber optic access such as Fiber to the Curb, Fiber to the Building, and Fiber to the Home is becoming more popular every year mainly used for the Internet access. Internet of Things (IoT) devices are connected to an Optical Network Unit (ONU) via wireless (WiFi, Zigbee, etc.) and/or wired (Ethernet, USB, etc.) communications. The connected IoT devices, such as sensors and video cameras, are networked to provide various functions and services. In general, these systems can only be used in environments where external electric power can be supplied to both the ONU and the communications equipment. These devices require power, which may be difficult to obtain depending on the location, such as natural environments such as mountains and rivers, outdoor activities in urban areas, etc. If these devices could be driven by electric power supplied via optical fiber, the range of applications would be even wider. Power over Ethernet is a simple single wired IoT system solution. But it is difficult to use in long-distance (over 100 m) environments or outdoors [1].

Another advantage of Power over Fiber (PWoF) is high resistance to disasters. Since optical fiber is a nonconductive power line, unlike electrical cables, PWoF helps to avoid lightning damage to electrical equipment connected to the optical fiber. However, the small core area of today's widely used silica-core optical fibers severely limit the available feed optical power [2], and the power that can be safely delivered from a single mode silica-core fiber (SMF) to an ONU is about 25 mW [3].

Hollow Core Fiber (HCF) is an innovative op- tical fiber that has the potential to break through the limitations of conventional optical fibers [4-5]. In conventional silica-core optical fibers, when the energy density becomes too high, fiber fuse occurs and burns inside of the fiber [6]. However, in HCF, light passes through air-core, which has nothing to burn, so no damage occurs even at energy densities much higher than conventional fibers. This feature enables transmission of large power, which could not be achieved with conventional silica-core fibers [7-9]. Utilizing these technologies, we are aiming to construct an IoT network driven solely by optical fiber power supply.

Since the power supply capacity of PWoF is still limited, it is also necessary to significantly reduce the power consumption of ONU devices and IoT devices. Deep sleep[10], which turns off the device power supply, has a significant power-saving effect, but there are problems such as the difficulty of controlling the timing of Deep sleep.

In this paper, we will provide an application drive dynamic sleep ONU and IoT system design. We have developed and implemented a power-saving algorithm for dynamic sleep of both ONU and IoT device. A prototype experimental system of the external power supply-less ONU and IoT application that can be driven solely by PWoF using HCF was examined and conducted power measurement experiments. In addition, the energy harvesting with PWoF was verified and its ability to drive an IoT system without an external power supply was also verified.

II. Dynamic sleep IoT PON System driven from IoT application

We proposed a method for coordinating passive optical network (PON) systems and IoT applications [11]. In this coordination, the power supply of the PON system and IoT applications is controlled in coordination so that the ONUs return from deep sleep mode in time with the data transmission of the IoT applications. The purpose of this system is to determine the sleep mode (deep or TRx) and sleep time/duration that satisfies the application connected to the ONU. Fig.1 shows the example of dynamic adaptive sleep schedule operation of the proposed method.

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First, the IoT application server obtains the transmission cycle of the IoT application. Next, the IoT PON Manager retrieves the transmission cycle from the IoT application server. The IoT PON manager then calculates the proper sleep time from the application's transmission cycle, selects a sleep mode (TRx sleep or Deep sleep) that matches that sleep time, and notifies the ONU via OLT. The ONU then executes the sleep operation according to the notified schedule. The above operation prevents IoT applications from sending data while the ONU is sleeping, thus preventing packet loss. Fig. 1 shows an example of adaptive sleep time setting based on the proposed method.

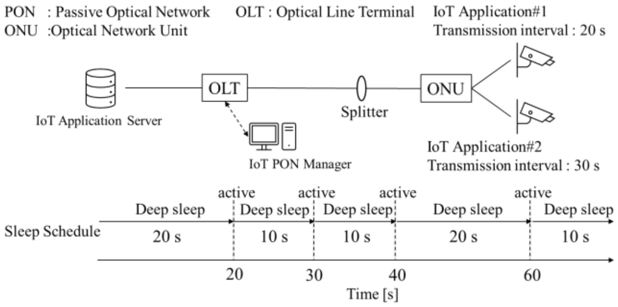

Fig. 1 IoT PON System linked to IoT applications and Example of an adaptive sleep schedule.

III. PROTOTYPE EXPERIMENTAL SYSTEM

Our goal is to build an IoT system that operates without an external electric power source using HCF. Furthermore, by combining the IoT PON system, we aim to realize a location-free and a power-saving system. As a first step, we created a prototype experimental system with the goal of operating the system using only PWoF. Therefore, the prototype system has two HCFs, one for PWoF and the other for IoT communications. For simplicity, we also created a Control Station that integrates the IoT Application server and the IoT PON Manager. Fig.2 shows the prototype experimental system configuration.

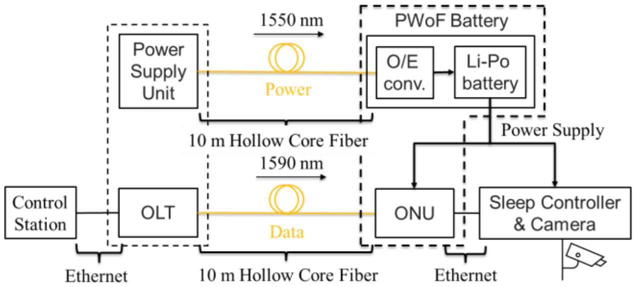

Fig. 2 Prototype experimental system configuration.

HCF is used for power supply and communication, with wavelengths of 1550 nm and 1590 nm, respectively. Originally, it was intended to multiplex the data communication and power feed wavelengths and transmit them over a single HCF, but two HCFs were used this time to simplify the configuration. Fig.3 shows the applied 10 m SC connecter spliced HCF. Fig. 4 shows the spectral characteristics of 500 m HCF, with three passband locations over 1510~1590 nm [12]. Therefore, we selected 1550 nm (power supply) and 1590 nm (communication) as the wavelength bands.

As a sleep controller, ESP32 microcontroller unit was used. ESP32 has a deep sleep mode that powers off almost all components, reducing power consumption to several tens of mW. An IoT application was realized by attaching a camera module to ESP32. The camera transmitted 800×600 pixel, 24-bit color images compressed in JPG format. The file size was approximately 20 KB. The reason for integrating it with the sleep controller was to make the configuration more power-efficient and simpler without a new microcontroller for camera control.

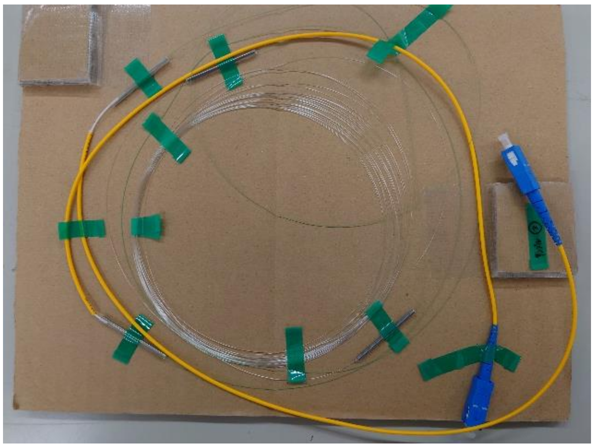

Fig. 3 10 m Hollow Core Fiber with SC connector.

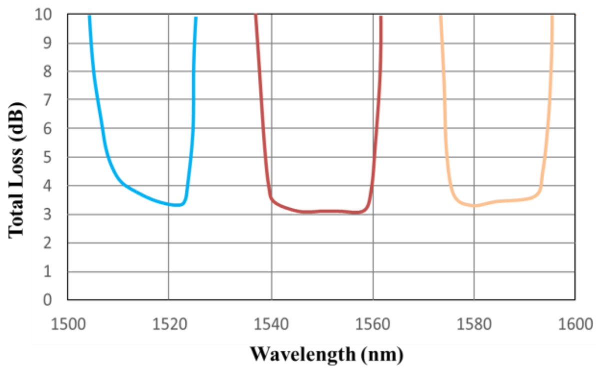

Fig. 4 Spectral characteristics of 500m HCF [12].

As an OLT and ONU, small Ethernet switch developing kits were used. Therefore, no PON protocols, such as gate, grant, etc., were implemented. Only sleep message transmission function was implemented. A deep sleep function is added to the ONU. Fig.5 shows the developed prototype device.

Fig. 6 shows the PWoF battery, which consists of an O/E converter and a 10,000 mAh Li-Po battery. Table Ⅰ shows the specifications of the PWoF battery.

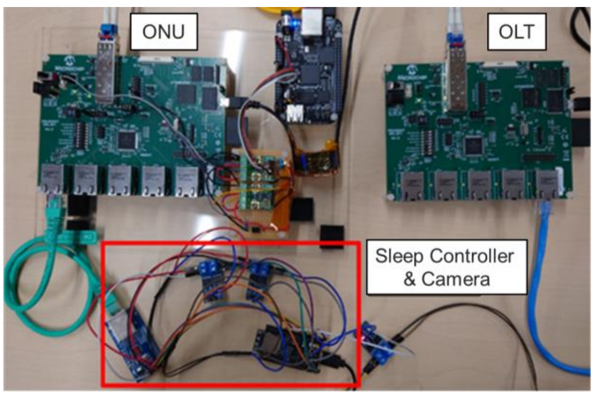

Fig. 5 Prototype ONU, OLT, sleep controller, and camera.

Fig. 6 PWoF Battery [13].

TABLE I. SPECIFICATIONS OF THE PWOF BATTERY

Item	Specification
Input optical power	Max. 500 mW
O/E conversion efficiency	Typ. 30%
Wavelength range	1300~1600 nm
Optical connector	FC
Output voltage	5 V
Output current	Max. 2 A
Battery	Lithium polymer
Capacity	10000 mAh

IV. IMPLEMENTED SLEEP ALGORITHM

Due to the limitation of the light receiving element, the PWoF battery can only input a maximum of 500 mW. Since the photoelectric conversion capability of the photodetector is about 30%, the power supply capability is about 150 mW. Therefore, we first implemented a dynamic sleep algorithm aimed at running the ONU and IoT application using only optical power supply. Fig.7 shows the flow of the implemented sleep algorithm to control deep sleep.

First, the camera takes a picture and transmits the data to the control station. When the transmission is complete, the sleep controller sends a Sleep Request to the control station. Upon receiving the Sleep Request, the control station notifies the Sleep Controller of the sleep time (T_{sleep}). The Sleep Controller then shuts down the camera and ONU, and itself enters a deep sleep state in which all components except the timer are shut down for the specified time (T_{sleep}). After time (T_{sleep}) elapses, the sleep controller wakes up and starts up the ONU; after waiting for the ONU to wake up for a period, the camera starts up and takes a picture. Thereafter, the same process is repeated.

V. EXPERIMENTAL RESULTS

We connected the power supply unit (External Cavity Laser and Erbium Doped Fibre Amplifier: Output up to 33 dBm) and the optical power meter with a 10 m HCF and checked the received power. When the output of the power supply unit was set to 30.8 dBm, the optical power meter received a power of 26.98 dBm (= 498.9 mW). Therefore, it was confirmed that the light power was received at about the input limit of the light receiving element. Approximately 3.8 dB of loss is incurred, but it is estimated that approximately 2.2 dB is incurred by the LC connector with SMF spliced to both ends of the HCF, and two FC/SC

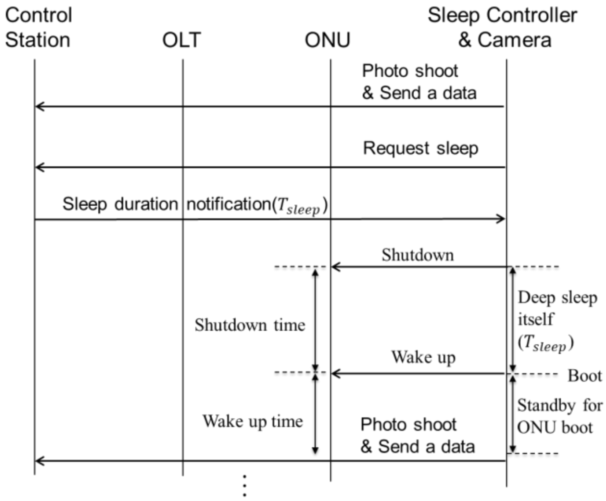

Fig. 7 Implemented sleep algorithm.

conversion connectors are used to connect the power supply unit and PWoF battery to the HCF, for a total loss of approximately 3.2 dB. Thus, the loss in the HCF itself is estimated to be about 0.6 dB. The loss of the 10 m HCF is 0.6 dB, but this is because it is a prototype HCF, and the 500 m HCF that was later installed on the campus is approximately 3 dB, including losses at the connectors at both ends. This gives us the prospect of extending the fiber to approximately 3.75 km when using EDFA, which is capable of 33 dBm output, and HCF, which is 500 m long and has 3 dB loss (including connector loss at both ends).

The power consumption of the prototype ONU and IoT application was measured. Power consumption was measured at the output of the Li-Po battery shown in Fig. 2. The results are shown in Fig. 8. The cycle is the time from when the system starts up, enters deep sleep mode, and then starts up again. Table II shows the results of 10 cycles of measurement of the time from system wake-up to completion of data communication (T_{active}), and the average power consumption(P_{active}) at that time. In this measurement, T_{active} was approximately 22 seconds. The P_{active} was 2845 mW and the maximum power consumption was 4,380 mW, and the power consumption(P_{sleep}) during deep sleep (T_{sleep}) was 42.1 mW.

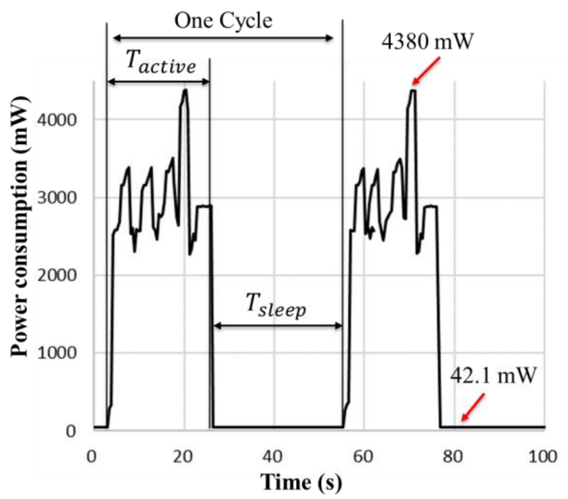

Fig. 8 Experimental result of power consumption in the ONU and camera.

TABLE II.
FLUCTUATIONS IN T_{active} AND ENERGY CONSUMPTION PER CYCLE

Cycle	T_{active} (s)	P_{active} (mW)	W_{active} (mWh)
1	22.19	2874.55	63786.26
2	22.17	2822.30	62570.39
3	21.70	2812.80	61037.76
4	22.31	2822.70	62974.44
5	21.70	2834.65	61511.91
6	22.64	2860.70	64766.25
7	22.51	2860.70	64394.36
8	22.63	2825.75	63946.72
9	22.22	2859.65	63541.42
10	22.67	2877.60	65235.19
Average	22.27	2845.14	63376.47
Standard deviation	0.34	22.74	1292.30

Total average power consumption per one cycle is calculated with the results shown in Fig. 8 as follows.

$$P_{average} = \frac{P_{tot}}{T_{active} + T_{sleep}} \quad (1)$$

$$P_{tot} = P_{active} \times T_{active} + P_{sleep} \times T_{sleep} \quad (2)$$

The experimental PWoF system can ideally supply 150mW (=500mW x 30%). If the average power consumption ($P_{average}$) is less than 150mW, the IoT system can operate continuously. We estimate that we can operate the system permanently by setting the deep sleep duration for 560 seconds or more with the values T_{active} , P_{active} in table Ⅱ and P_{sleep} in Fig. 8 . However, in actual systems, PWoF may not be possible to supply the 150 mW due to the connection loss of the O/E converter or loss in battery charging. For this reason, we investigate the amount of power that could be supplied in actual operation.

In order to operate system permanently, the real amount of electricity supplied to the battery is required. The charging efficiency was also calculated from the obtained W_{real} and W_{ideal}.

$$\text{Charging efficiency} = W_{real}/W_{ideal} \quad (3)$$

Here, W_{real} is the real-energy charged to the battery and W_{ideal} is the ideal-energy charged to the battery.

The energy charged to the battery (W_{real}) is calculated as follows.

$$W_{real} = P_{tot} \times N_{diff} \quad (4)$$

Here, N_{diff} is the difference in the number of times the system can be started with a single power charge when using PWoF and when not using it.

The amount of power (W_{ideal}) that should have been supplied under ideal conditions was also calculated as follows.

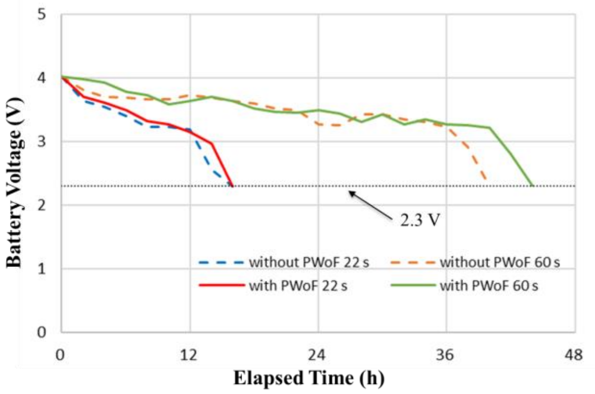

Fig. 9 Changes in battery voltage.

$$W_{ideal} = 150 \times (T_{active} + T_{sleep}) \quad (5)$$

we evaluates how long the system can be driven with the full charged battery and PWoF. Experiments were conducted with two wake-up intervals of 22 seconds ($T_{sleep} = 0$) and 60 seconds ($T_{sleep} = 38$) with/without PWoF. Fig. 9 shows the results of the battery voltage measured every two hours; the PWoF battery was 4.01 V at full charge. The voltage was approximately 2.3 V when the system stopped working. Table Ⅲ shows the system drive time depending on wake-up interval and with/without PWoF. We can see drive time with PWoF is longer than that without PWoF.

TABLE III. SYSTEM DRIVE TIME WITH AND WITHOUT PWOF

PWoF	Wake-up interval (s)	Driven time (h)
Without	22	14.5
With	22	15.1
Without	60	41.3
With	60	45.9

Table Ⅳ shows calculated Charging efficiency. When the wake-up interval was 22 seconds, the charging efficiency was 80%; when the wake-up interval was 60 seconds, the charging efficiency was 71%. In both cases, the charging efficiency was not 100%, indicating that 70~80% of the power was obtained compared to the ideal state.

TABLE IV.
CHARGING EFFICIENCY CALCULATED FROM THE DIFFERENCE IN NUMBER OF DRIVES WITH AND WITHOUT PWOF

Wake-up interval (s)	N_{diff}	W_{ideal} (mWh)	W_{real} (mWh)	Charging efficiency
22	104	2,270	1,814	80%
60	276	6,880	4,862	71%

Fig. 10 shows the total average power consumption of the entire system when T_{sleep} is varied. In the case that the charging efficiency is 70% (=105mW) and the cycle is set to 982 seconds ($T_{sleep} + T_{active} = 960 + 22$), the average power consumption exceeds the power supply capacity, so continuous operation is possible.

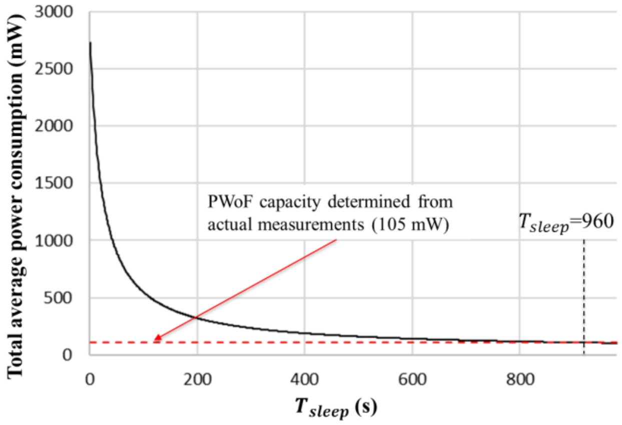

Fig. 10 Change in total average power consumption of the ONU and IoT application with T_{sleep}.

TABLE V. VARIABLE LIST

$P_{active/sleep}$	Power consumption during active/sleep (mW)
$T_{active/sleep}$	Active/sleep duration (s)
W_{active}	Amount of power consumption during Active(mWh)
N_{diff}	Difference in the number of system drives with and without PWoF
P_{tot}	Total energy consumption per cycle (mWh)
W_{real}	The energy charged to the battery by PWoF (mWh)
W_{ideal}	Energy that should be charged (mWh)

We examined the reasons why the charging efficiency did not reach 100%. First, we suspected that the power consumption of the ONU and camera fluctuated from cycle to cycle. However, Table Ⅱ shows that neither $P_{average}$ nor W_{active} varied significantly, suggesting that the effect of power consumption variation from cycle to cycle was small.

Other possible causes include the O/E converter's inability to perform as per the spec sheet, losses incurred when boosting the voltage to 5 V for output from the battery to the device, and losses incurred when charging the battery. However, since the PWoF battery does not have the ability to display the power after photoelectric conversion, the cause could not be determined.

VI. CONCLUSION

A low-power IoT system that operates only with Power over Fiber using Hollow Core Fiber was designed and an experimental system was prototyped. As a result, we confirmed that the average power consumption of 150 mW was sufficient to drive the system once every 10 minutes and to transmit image data. However, when the system was actually driven by PWoF, it was confirmed that the system could not supply 150 mW as ideal, and the power supply capacity was about 70~80% of the ideal state. This means that when the system is actually operated, the system is driven once every 16.3 minutes.

In the future, we would like to multiplex the wavelengths of data and energy and transmit them in a single HCF, further improve the capability of PWoF by improving or increasing the number of photodetectors and implement an algorithm to adaptively adjust the sleep time in the experimental system as proposed in [11].

ACKNOWLEDGMENT

This research includes the results conducted under the "Research and Development of Advanced Optical Transmission Technologies for Green Society (JPMI00316)" of the Ministry of Internal Affairs and Communications (MIC) of Japan. The authors are grateful to KEIO future photonic network Open Lab for providing experimental facilities. Authors also appreciate for members in Furukawa Electric for providing HCF.

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