UWB-based Positioning and Transmission System by Power-Over-Fiber with Signal

Guangxin Li
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
liguangxin@bupt.edu.cn

Yuemei Li
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
liym@bupt.edu.cn

Xueliang Gu
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
xueliang_gu@bupt.edu.cn

Zhiguo Zhang
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
zhangzhiguo@bupt.edu.cn

Tong Zhai
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
zhai_tong@bupt.edu.cn

Rui Zhou
State Key Lab of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
xiao12rui@bupt.edu.cn

***Abstract*—An ultra-wideband positioning and transmission system is proposed based on the co-transmission of signal and power by optical fiber. The system achieved 1Hz frequency positioning when the output optical power was relatively low.**

Keywords—Power-Over-Fiber with signal, Ultra-Wideband w ireless transmission, location estimation, Data transmission, Und erground Transmission Pipeline Gallery

I. Introduction

With the rapid development of society, safety monitoring of underground corridors in power systems has drawn widespread attention. The underground pipe gallery's transmission line is considered a vital transmission method, and its safety directly determines the power enterprise's development[1].

The transmission pipeline gallery of the power system is typically located at a depth of approximately 10 meters underground and is constructed with reinforced concrete. The interior of the pipeline gallery is an enclosed space, and electromagnetic communication waves from the surface cannot penetrate the interior of the pipeline gallery. However, the power system must arrange for electric personnel to inspect the power lines in the pipe gallery. Therefore, the internal inspection personnel of the pipe gallery cannot effectively interact with the outside world. And external personnel cannot grasp the location and movement of the inspectors in real-time. In the current power transmission pipeline corridor, the predominant approach to monitoring internal personnel activities is to deploy video surveillance systems which require a stable and high-speed transmission environment.[2-4].

Optical fiber communication is characterized by long transmission distance, swift transmission speed, low transmission loss, strong anti-interference ability, and low laying cost. With the rapid advancement of optical fiber communication technology, the use of optical fiber for energy transmission has emerged as a research focus. Power-over-fiber (POF) technology uses lasers to provide electrical energy to remote electrical appliances through the optical fiber. POF is highly immune to electromagnetic interference and electric shock, making it suitable for harsh environments. And the co-fiber transmission of energy and data lasers is feasible when transmitted at different wavelengths, enabling shared energy and information. The PoF technology can effectively address power supply issues and long-distance data transmission for commercially available sensors. Recently, POF technology has been applied in various industries, such as icing monitoring of overhead transmission lines and seabed observation[5-6].

Ultra-Wide Band (UWB) is a critical technology with broad application in indoor positioning. UWB boasts a bandwidth exceeding 500MHz, which provides a data transfer rate surpassing 100Mbps, making it a favorable option for near-field data transmission. Moreover, the high bandwidth and ultra-short pulse shape of UWB technology can reduce the effects of multipath interference and allow it to penetrate obstacles such as walls and objects. Currently, indoor positioning based on UWB technology can achieve positioning with an error under the centimeter level [7-10].

We have proposed a novel system combining the POF and UWB positioning systems. The system can monitor the real-time position and movement posture of mobile positioning targets in the pipeline corridor and perform simple information exchange and other features with the handheld terminal carried by the mobile positioning target. The proposed system can be deployed in the underground utility corridor, even in harsh environments, without any concerns about powering the sensors or long-distance data transmission. As we utilize the existing Optical Ground Wire (OPGW) on the power transmission system, only a tiny amount of additional optical fiber is required to build the system. The system solves the problem of communication and monitoring internal personnel activities in the underground transmission pipeline gallery in the power system. This innovative system promotes the broader application of POF technology and contributes to technological progress in the industry.

II. SCHEME

Figure 1 shows the UWB-based positioning and transmission system schematic diagram based on fiber-optic energy-signal co-transmission. The proposed system comprises four parts: server, demodulator, anchor nodes, and handheld terminals. The anchor nodes and data demodulator

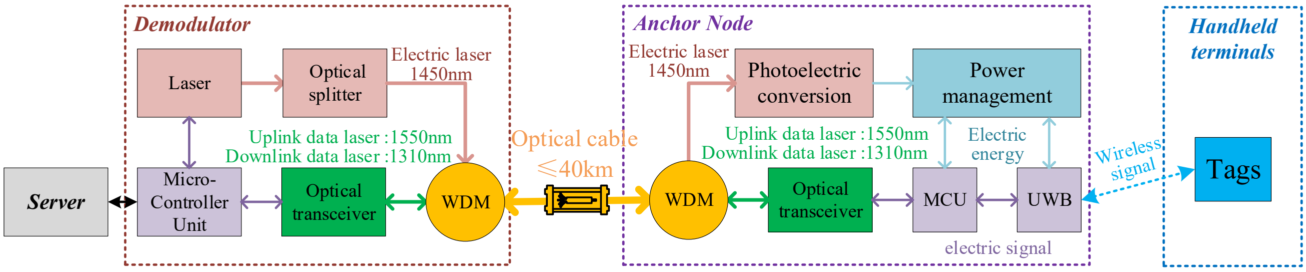

Figure1 The schematic diagram of the UWB-based positioning and transmission system based on power-over-fiber with signal

utilize a single-mode fiber as the transmission channel for laser energy and data, InGaAs as the photoelectric conversion unit, and the ultra-wideband wireless communication modules to acquire the required distance value for position estimation. The server and data demodulator can be installed in the substation using the idle fibers in the OPGW for power and signal co- transmission. The anchor node was established in the underground transmission pipeline gallery, while the target positioning personnel carried the handheld terminal.

In this system, the energy light utilizes a wavelength of 1450nm, while two laser wavelengths, 1310nm, and 1550nm, are used for information transmission due to the two-way communication involved. The 1310nm laser is used for the server to transmit information to the anchor nodes. The 1550nm laser is used for the anchor nodes to send data to the server. The anchor nodes report to the server the real-time distance information between handheld terminals and anchor nodes and the knowledge that handheld terminals need to send to the server.

Data processing algorithms and information interaction platforms are primarily deployed among the servers in this system. The server is connected to the demodulator via a network cable. After receiving the processed packaged data uploaded by the data demodulator, the server estimates the position of the target positioning node based on the distance data and displays it on the relevant interface. The server is also responsible for information exchange between the server and the handheld tag-end personnel. It shows the uploaded information data of the handheld terminals and can customize the sent data.

The demodulator of this system mainly consists of a laser source and a data processing unit, which is responsible for receiving the data uploaded by the anchor nodes, packaging and uploading it to the server after processing, and forwarding the server's data to the anchor node. The data processing unit has multiple optical transceiver modules, with each optical transceiver module corresponding to each anchor node. Multiple optical transceiver modules are uniformly controlled and managed by a microprocessor. The laser source emits a 1450nm laser, coupled with the information light in WDM, and transmitted to the anchor nodes via single-mode fiber after passing through the optical splitter.

The anchor node of this system is mainly composed of a photoelectric conversion unit, a UWB module, a low-power microprocessor, and an optical transceiver module. The photoelectric conversion unit converts the energy laser into electrical energy and stores it in the supercapacitor to supply power to the base station node. The SPI peripheral of the low-power processor drives the UWB module to transmit and receive wireless data and communicate with the host computer. The optical transceiver module forwards the data of server and handheld terminals.

The handheld terminals mainly consist of UWB modules, low-power microprocessors, and human-computer interaction components. The UWB module completes the external information exchange and ranging functions. The human-computer interaction component includes an OLED for displaying the data sent by the server and the current position and four buttons to transmit different information.

In the entire information interaction process, the anchor nodes and the handheld terminals interact with the ranging information at 1 Hz. After the anchor nodes calculate the distance of the handheld terminals, it reports the information to the server. The server uses the distance data to estimate the current position of the handheld terminals. Suppose an information transmission request occurs during the ranging process. In that case, an additional information transmission process will be performed, and multiple handshakes will be used to ensure the reliability of the information transmission process.

III. Position Estimation And Data Transmission

A. *Realization of position estimation*

The system needs to be processed with low power consumption due to the power limitations of the single-mode optical fiber in the power-over-fiber system and the photoelectric conversion efficiency. As the UWB module needs to consume much unnecessary power in the continuous receiving state in the idle state, all information exchange in the entire system is initiated by the anchor node to ensure the reliability and stability of the communication, as well as to meet the low power consumption requirements of the power-over-fiber system.

This system’s range principle, Lee-TWR, is based on a modified version of the TWR (Two Way Ranging) ranging method, as illustrated in the flow chart in Figure 2. The handheld terminals must constantly be receiving to initiate the ranging process. All anchor nodes broadcast the positioning *start message* (start) at the start of the ranging process. Once the handheld terminals receive this message, the complete ranging process officially begins. At the end of each Lee-TWR process, the anchor nodes enter a sleep mode and automatically restart at the beginning of the following positioning process. Due to the high communication rate of the UWB module, each data packet can be transmitted within 1 ms, and the entire Lee-TWR ranging process takes less than 20 ms. Therefore, the anchor nodes can save more than 80% of power consumption, thus meeting the low power consumption requirements of the system.

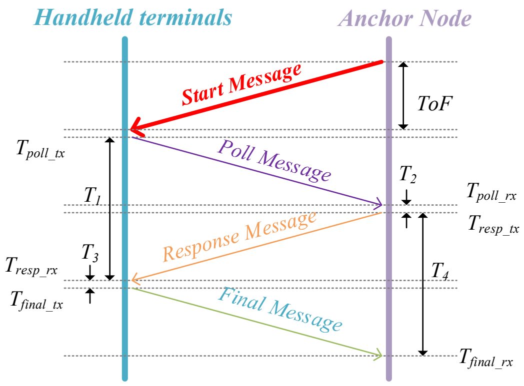

Figure2 Schematic diagram of ranging process of Lee-TWR

According to Figure 2, a total of six time stamps can be obtained, consisting of three time stamps for the handheld terminals T_{poll_tx}、T_{resp_rx}、T_{final_tx} and three time stamps for the anchor node T_{poll_tx}、T_{resp_rx}、T_{final_tx}. We can obtain the intervals T_1 and T_4 for the UWB module to send messages, and the time T_2 and T_3 which is taking to receive, process and send messages. The electromagnetic wave flight time ToF(time of flight) between the two points required for distance measurement can be calculated from this.

$$ToF = \frac{T_1 - T_2}{2} = \frac{T_4 - T_3}{2} \tag{1}$$

$$ToF = \frac{T_1 \times T_4 - T_2 \times T_3}{T_1 + T_2 + T_3 + T_4} \tag{2}$$

The time of flight (ToF) can be measured to obtain the distance between the anchor nodes and the handheld terminals using Lee-TWR ranging. This distance value is multiplied by the speed of light constant to determine the precise distance. The approximate location of the target positioning node can be estimated once the server receives the distance value successfully.

Generally speaking, we will get the distance values from the handheld node to the two anchor nodes, and the problem now becomes solving the arc intersection problem shown in Figure 3. After calculating the current two-dimensional coordinates of the handheld terminal on the two-dimensional graph, project it onto the connecting line of the two anchor nodes to obtain the current one-dimensional coordinates of the handheld terminal.

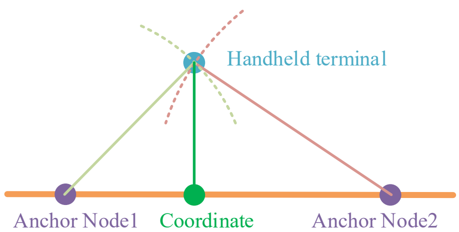

Figure3 Schematic diagram of location estimation method

B. Realization of data transmission

The server stores the anchor nodes closest to the handheld terminals and updates them after each successful positioning. For data transmission, short data is loaded in the Lee-TWR data flow, where uplink data is loaded in the *Final Message*, and downlink data is loaded in the *Response Message*. However, if the data exceeds 1 Kbytes, an additional data-sending process similar to the Lee-TWR process will ensure the stability and reliability of the information transmission process based on multiple handshakes.

IV. Result And Discussion

A. Low Power Verification of Lee-TWR

Firstly, power consumption reduction verification is conducted for the Lee-TWR method. The current of the anchor node is collected using a power analysis instrument in two working modes, TWR and Lee-TWR, at a frequency of 3MHz. Figure 4 displays the results. Due to the high speed of Ultra-Wideband (UWB) technology, the ranging process is completed quickly. The microcontroller unit (MCU) performs data processing, and then the optical transceiver module is turned on to send the data back.

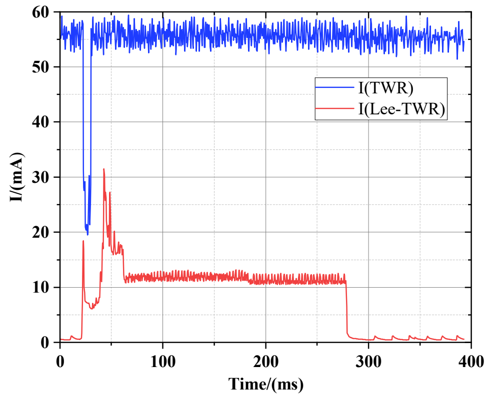

Figure4 Power consumption comparison of TWR and Lee-TWR

The blue curve represents the current consumption in TWR mode. Because in this way, the anchor node needs to be always on, and the electrical appliances with higher power consumption, such as UWB modules and optical transceiver modules, are always in a normal working state, so their current is always at a high level. Among them, in the process of ranging, the monitoring function of the UWB module is turned off, so there will be a current trough phenomenon at this time. The red curve represents the current consumption in the improved Lee-TWR mode. This process is designed to turn on all high-power electrical appliances sequentially, significantly reducing power consumption by more than 85%. In this way, each electrical appliance is turned on sequentially and enters a dormant state after a job is completed, which greatly reduces power consumption, with almost zero current consumption in the sleep state. The UWB technology's fast communication rate and power-saving design ensure that the system meets the low power consumption requirements of the power-over-fiber system. And since all information exchanges in this way are initiated by anchor nodes, there will be no information loss, and the reliability and integrity of the information under low power consumption conditions will also be guaranteed.

B. Power supply verification of energy transfer system

Using a 1450nm laser, an energy laser was emitted and passed through a 20km fiber optic, resulting in an optical energy power of about 50 mW at the anchor node. The anchor node was programmed to measure the distance once every second and send a message back accordingly. After approximately 151 hours of testing, the anchor node generally operated with the stable output voltage from the energy management unit, and a total of 545871 valid distance values were returned.

C. System verification

Four anchor nodes were installed in an indoor corridor that is approximately 100m in length, with about 30m between each node. A bundle of four-core optical cables connects the demodulator to each anchor node. Once the system runs, handheld terminals are tested in four fixed positions (5m, 31m, 50m, 85m), and 4800 data are collected each time. The error distribution diagram of each position estimation is shown in Figure 5.

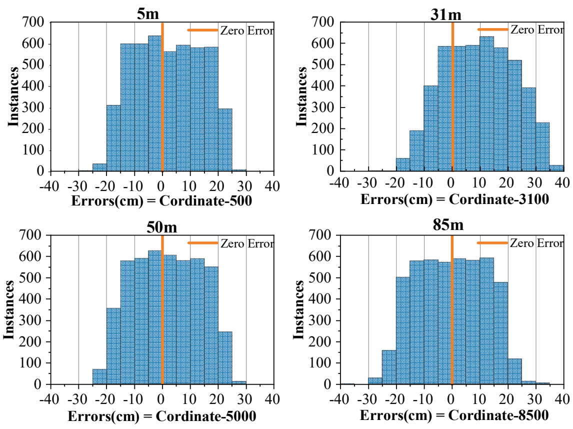

Figure5 Error distribution map of four positioning

It is evident from Figure 5 that the system has an overall error of about 20cm when using only a relatively small energy laser to perform functions. Specifically, when the distance between the handheld terminal and anchor node is 1m, the tag can receive ranging data from up to three anchor nodes, resulting in a more significant error than the remaining distances.

Overall, the test results show that the system can run stably, and can achieve positioning results with an error of about 20cm in narrow indoor corridors

V. CONCLUSION

To solve the problem of ineffective communication in the power system's underground transmission pipeline gallery and ensure inspection personnel's safety in production and maintenance, we combine POF and UWB positioning and propose an UWB-based positioning and data fusion transmission system for underground transmission pipelines. Although the POF system is limited by the energy attenuation problem of long-distance transmission, the power consumption of the entire system has been optimized to 50mW under the condition of deplorable optical fiber transmission loss, which was possible to achieve positioning at a frequency of 1Hz when two anchor nodes were 30m apart and could transmit short messages simultaneously.

The system effectively solves the communication problems between personnel in the underground power transmission pipeline corridor and inside and external personnel. It allows external personnel to grasp the real-time location information of personnel inside the pipeline corridor. Through this system, the safety and efficiency of the inspection staff of the underground pipe gallery can be effectively improved. It provides a promising solution for maintaining and monitoring the underground pipe gallery in the power industry and has rich use value in the power industry. In future research, additional sensors can be added based on this system to monitor the environment of the underground utility corridor to enhance the practical value of the system further.

ACKNOWLEDGMENT

The research project was carried out with the NSFC under Grant 62075017.

REFERENCES

[1] W. Bai, Y. Wu, C. Lu, Y. Lu, and C. Zhong, "Channel modeling by ray tracing for city underground power pipe gallery," 2021 7th International Conference on Computer and Communications (ICCC), Chengdu, China, 2021, pp. 1383-1388.

[2] Noorain, Soubia, M. Mamtha, and Z. Jabeen. "Underground cable fault detection using a robot." International Research Journal of Engineering and Technology (IRJET) 5.05 (2018): 2395-0056.

[3] S. Xu, W. Liu, Z. Li, and Y. Du, "Information node positioning system of underground pipe gallery based on CAN internet of things technology," 2021 4th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA), Suzhou, China, 2021, pp. 170-175.

[4] X. Zhuang, S. Chen, J. Wu and C. Wang, "Underground comprehensive pipe gallery illegal intrusion wireless sensing system," 2018 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), Qingdao, China, 2018, pp. 1-5.

[5] Q. Mei, X. Gu, R, Shen, G. Li, Y. Li, and Y. Qin, "Meteorological monitoring system for transmission line tower based on power-over-fiber," 2023 the 6th International Conference on Energy, Electrical and Power Engineering (CEEPE), Guangzhou, China, 2023, in press.

[6] Y. Li, S. Chang, H. Zhang, S. Cai, and Z. Zhang, "28km long-distance transmission of high-power laser over few-mode/single-mode fiber system", Proc. SPIE 12169, Eighth Symposium on Novel Photoelectronic Detection Technology and Applications, 121695B (27 March 2022).

[7] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. Al-Ammar, and H. Al-Khalifa, "Ultra wideband indoor positioning technologies: analysis and recent advances." Sensors 16.5 (2016): 707.

[8] Sahinoglu, Zafer, S. Gezici, and I. Guvenc. "Ultra-wideband positioning systems." Cambridge, New York (2008).

[9] Mazhar, Fazeelat, MG. Khan, and B. Sällberg, "Precise indoor positioning using UWB: A review of methods, algorithms and implementations." Wireless Personal Communications 97.3 (2017): 4467-4491.

[10] Duru, Anday, E. Şehirli, and İ. Kabalcı. "Ultra-wideband positioning system using twr and lateration methods." Proceedings of the Fourth International Conference on Engineering & MIS 2018. 2018.