Experimental study on long-distance SPAD-based VLC systems

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Abstract. Long-distance visible light communication (VLC) based on single photon avalanche diode (SPAD) can supplement the existing wireless communication mechanism in many senarios. Although there are many researches on VLC in recent years, the experiments on long-distance VLC are relatively scarce. In this paper, we use the experimental method to study the long-distance VLC, so as to apply it to two new application scenarios — VLC between buildings and in mountainous areas. A system model is established for both of the scenarios. Based on the model, a low energy consumption device for long-distance VLC is completed to realize the long-distance transmission of voice and data. At the end of the paper, we simulate the performance of the proposed system. The results indicate that the system is feasible to realize the duplexing voice and data transmission within the range of 2 km when the data rate is below 200 kbps.

1. Introduction
Visible light communication (VLC) is based on the high-frequency flash of light-emitting diode (LED), which makes it has the advantages of sufficient frequency resources, energy conservation and environmental protection compared with traditional wireless communication, thus, it is easier to achieve the goal of higher speed and lower energy consumption using VLC. However, as visible light is located in the terahertz band, its energy decays sharply in space, so the long-distance VLC has always been a perplexing problem. Since single photon avalanche diode (SPAD) can detect optical signals on photon, it greatly improves the sensitivity of the VLC receiver [1–4]. Therefore, we use SPAD to realize the application of VLC in two typical long-distance scenes.

Outdoor VLC is mainly affected by atmospheric absorption and turbulence, etc. Under weak atmospheric turbulence, the channel of long-distance VLC can be characterized by Lognormal model [5]. Up to now, the research on VLC focuses on indoor transmission, and there are few experiments on outdoor long-distance VLC. Most of the engineering implementation processes of long-distance VLC focus on underwater communication [6,7] and lighthouse communication. China has achieved real-time underwater communications with a distance of 1,244m and a data rate of 1Mbps. Japan has implemented one-way lighthouse communication with a data rate of 1,022 bps and a transmission distance of 2 km.

In this paper, firstly we introduce two kinds of application scenarios of long-distance SPAD-based VLC which are not well performed by using traditional wireless communication methods. We establish a SPAD-based VLC system model to meet the specific requirements of communication. Based on the model, we devise a new kind of long-distance duplexing VLC...
device. Finally, in order to verify the feasibility of the scheme, we simulate the proposed system under different communication distances and data rates.

2. Application scenarios
We apply the long-distance VLC based on SPAD to the scene as shown in figure 1 and figure 2. In the first scenario, VLC is used to realize high-speed voice and data transmission between buildings, so as to overcome the poor quality of communication service caused by electromagnetic shielding and reflection of tall buildings. In figure 2, SPAD-based VLC is applied to mountainous areas where the base station layout is not very practical. The using can be of certain significance to field research and rescue work etc in practice.

Figure 1. Diagram of inter-building VLC.

Figure 2. Diagram of VLC in mountainous areas.

To some extent, long-distance SPAD-based VLC can complement the traditional wireless communication. It can solve the wiring difficulties, electromagnetic interference, inconvenient construction of base stations and other problems. Meanwhile, it has the advantages of higher quality, lower cost, easier installation and more safety, etc. Furthermore, on the basis of point-to-point communication, multiple VLC transceivers can be used to form a network to achieve communication coverage in more areas.
3. System model of long-distance VLC

The model of the long-distance VLC system we develop is shown in figure 3 [8, 9]. The input voice or digital signals become bitstreams to be sent after the pre-processing process such as analog-to-digital conversion, encoding and framing etc. After on-off keying (OOK) modulation, the LED transmitter sends out optical signals. At the receiving terminal, the optical signals are detected by SPAD detector after the convergence of optical lens, after which the converted electrical signals are judged. Finally, the signals are output through decoding, digital-to-analog conversion and other processes.

Figure 3. The system model of long-distance VLC.

4. Experiment and system setup

4.1. The structure of the long-distance VLC device

In order to meet the requirements of the proposed scenarios, we completed a long-distance SPAD-based VLC device, which can be used to realize voice and data transmission within the range of 0.4~2 km. The average power consumption of the device is 0.5 watts.

Figure 4. Long-distance wireless VLC device.
As is shown in figure 4, in addition to the optical signal transmitter and receiver, the device also comprises a sighting telescope for the optical alignment between the sending and receiving ends. There is a supply hub, a data interface, a headset jack and a power indicator on the back of the device. They are set up to connect to some external devices or display the status of the system. The corresponding receiver and transmitter parts are aligned using the telescope to realize real-time duplexing communication as in figure 5, but the distance between them will be much greater than the figure shows in practice.

4.2. The working process of long-distance VLC device

Figure 6 is the block diagram of the device, which is mainly composed of ARM+AEM2000 platform, FPGA platform, optical front-end circuit board and some peripherals and interfaces. It adopts OOK modulation and Reed-Solomon (RS) codes. Users can transmit voice signals through microphone (MIC). After the processing of AEM2000 and advanced RISC machine (ARM), the signals are sent to data interface via universal asynchronous receiver/transmitter (UART). Then for transmitting purpose, the frame handle (FH) is available for framing. Finally, the switch driver circuit controls LEDs to flash to transmit signals based on the modulated electrical signals. Data transfer can also be achieved through Serial Peripheral Interface (SPI)
or UART which is directly connected to the data interface, and the rest of the process is basically the same as voice transmission.

When receiving data, the optical signals enter the device after the convergence of the lens. The light is perceived by SPAD and then stirs up electrical signals. Subsequently, the signals are amplified by trans-impedance amplifier (TIA) and differential amplifier, and then determined by comparator. After that, the frame structure of signals is removed by FH and bitstream data can be transmitted to the data interface, which are then received through SPI or UART for data or converted into voice by ARM+AEM2000 platform and played through headset.

What is more, further improvements will be made on ARM to increase the functions of the device and enhance its adaptability in different scenarios.

5. Simulation results and discussions
In order to verify the feasibility of the proposed scheme, we made a simulation of the bit error rate (BER) under different data rates and communication distances, as is shown in figure 7. The simulation uses Lognormal model to depict the long-distance propagation of light in free space.

![Figure 7. BER under different propagation distances.](image)

Obviously, when the communication distance is about 2 km, a relatively reliable data transmission under the rate of 200kbps can be achieved. It is noticeable that the simulation is implemented without channel coding, and the signal decision mode has been greatly simplified [10], which means that the performance of the actual system still has room for improvement. However, the channel and electronic device is relatively ideal, thus the actual performance may be of some difference from the simulation result.
6. Conclusion
In this paper, we applied the long-distance SPAD-based VLC in two new scenarios: inter-building communication and mountainous belt communication. We built a system model in these two scenarios, based on which a long-distance VLC device has been designed. The results of the simulation indicate that the system is feasible within the communication distance of 2 km and under the data rate of 200 kbps.

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