High-Speed Optical Wireless Communication System for Indoor Applications

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***Abstract*—A novel high-speed optical wireless communication system for indoor personal area networking applications is proposed and studied. A proof-of-concept experiment at 12.5Gbps wireless transmission has been successfully demonstrated with limited mobility. When integrated with WiFi-based localization system, high-speed optical wireless communication with mobility feature can be achieved over the entire room. The performance tradeoffs between the maximum beam footprint and overall bit rate has also been studied and quantified experimentally and the results show that error-free (BER<10^{-9}) reception can always be achieved for a wide range of bit rates from 1Gbps to 12.5Gbps.**

***Index Terms*— Broadband communication, fiber optics links and subsystems, indoor optical wireless communications, personal communication networks.**

I. Introduction

WIRELESS communication systems are attractive because of its capability to provide mobility to end users. Compared with the traditional radio frequency (RF) technology and millimeter-wave systems, optical wireless (OW) technology has multiple advantages, such as the unregulated large bandwidth available, immunity to electromagnetic interference, and the possibility of frequency reuse and security at physical layer where optical beam does not penetrate walls or opaque objects [1]. Therefore, for over one decade OW communication for indoor applications has attracted considerable attention [2-7].

Optical wireless (OW) communications can be generalized into two groups: the diffused system and the line-of-sight (LOS) system [2]. The former utilizes totally diffused beam that covers the entire service area and provides mobility functionality to subscribers. However, the diffused system suffers from severe multipath dispersion which limits the transmission bit rate and also it is not energy efficient [3]. On the other hand, the direct LOS system employs a narrow laser beam to establish a point-to-point transmission link between the transceivers; thereby the transceivers must be spatially fixed to satisfy the strict alignment requirement. Therefore no mobility can be provided in this scheme in spite of its potential of providing extreme high transmission bit rate.

To take advantage of both kinds of OW systems, we have recently proposed a novel OW system for indoor personal area networking applications and have experimentally demonstrated error-free (BER<10^{-9}) transmission of up to 2.5Gbps [8-10]. The concept used by us is similar to the “hotspot” proposed by D.C. O’Brien et al. [4], however instead of using a separate light source in each “hotspot”, we proposed the ceiling mounted fiber transmitter which is simply composed by a fiber end, a lens and a steering mirror. All these fiber transmitters are connected to a central office (CO) by a fiber distribution network and multiple rooms can be served by a single CO. All the complex functions and expensive devices are located in the CO to reduce the cost. We also proposed to incorporate WiFi-based localization function with the OW system and it enables dynamic change of the beam position to provide ubiquitous coverage of the entire room. It should also be noted that recently a remarkable 1.25Gbps indoor cellular OW communication has been experimentally demonstrated [5]. However, an angle-diversity receiver was used and three transmitters and receivers were needed for each user. In this paper, we further improve our system to 12.5Gbps communication. We also experimentally investigate and quantify the tradeoff between the maximum beam footprint and achievable bit rate of our proposed OW system.

II. System Structure

Our proposed system consists of a CO that centrally processes and distributes the optical signal to a number of access points via an optical fiber feeder network. The CO also acts as a gateway to the external network. In the access point, the fiber end is the transmitter and it is incorporated with a localization function to provide ubiquitous coverage over a 4m×4m×3m room. With the localization information of the subscriber, comparatively wider divergent beam is employed to cover that user’s position and its surrounding areas. Therefore both high speed data transmission using direct LOS link as well as limited mobility can be provided. When the user moves out of that area, which can be identified by the localization system, the signal light is then directed to the new position, resulting in

Manuscript received January 4, 2011. This work was supported in part by NICTA. NICTA is funded by the Austrailian Government as represented by the Department of Broadband, Communications and the Digital Economy and the Australian Research Concil through the ICT centre of Excellence program.
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mobility over the entire room. The redirection of signal is realized by the proposed ceiling mounted fiber transmitter, as shown in Fig. 1. This fiber transmitter consists of a fiber end, a lens and a steering mirror. The lens is used to increase the divergence of the signal beam to cover a certain area and the steering mirror is used to change its orientation according to the localization information. At the receiver end, a compound parabolic concentrator (CPC) pointed straight up is employed to collect the signal before detection with a photodiode (PD) directly [9].

The localization function can be realized through a number of different methods, such as WiFi-based [11], Zigbee-based system [12] and infrared-sensor-based [13]. We have chosen the WiFi-based localization scheme in our system for its low-cost and easily available nature. Furthermore our system does not require precise location which is also more suited to the WiFi-based localization system.

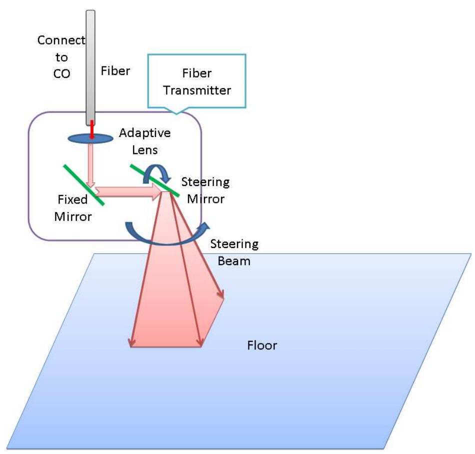


Fig. 1. System structure.

The room considered is a realistic office scenario consisting of two rectangular cubicles with strong background lamps. All the partitions are opaque therefore the incident signals are either absorbed or blocked. Furthermore, the cubicles are equipped with tables, chairs and other office equipments. It is obvious that in such a scenario, shadowing due to physical obstacles result in the worst signal reception and strong lamps creates an environment of worst case background light. However as the fiber transmitter is located just above the interactions of the two adjacent cubicles, direct line-of-sight (LOS) channel is always available.

III. Experiments

The setup of our experiments is illustrated in Fig. 2. Since the WiFi-based localization system has been intensely studied and demonstrated, we will only focus on the optical wireless transmission. The wavelength of the transmitted optical signal is generated in a CO with a DFB laser at 1550.12nm and it is modulated using 12.5Gbps 2^{31}-1 PRBS data in on-off-keying (OOK) modulation format. The modulated signal is transmitted to the access point via 5.6km standard single mode fiber. Then this signal passes through a lens to increase its divergence before propagating in free space. At the subscriber end, the signal is captured by a CPC with 45^{o} field-of-view and detected by a PD (PIN with 11.5GHz electrical 3dB bandwidth and 0.8A/W responsivity at 1550nm). Here a small sensitive area PD (0.5mm diameter) and a coupling system consisting of multiple lenses and a fiber collimator (NA=0.49) are used instead of a large sensitive area PD due to our device limitation. A coupling loss less than 2dB can be achieved by carefully adjustments. Then the received data is then amplified with an 18dB gain 25GHz amplifier and measured using a bit error rate tester (BERT) and a broadband digital communication analyzer (DCA). The measurement in our experiment has also included the strong background light from the overhead lamps.

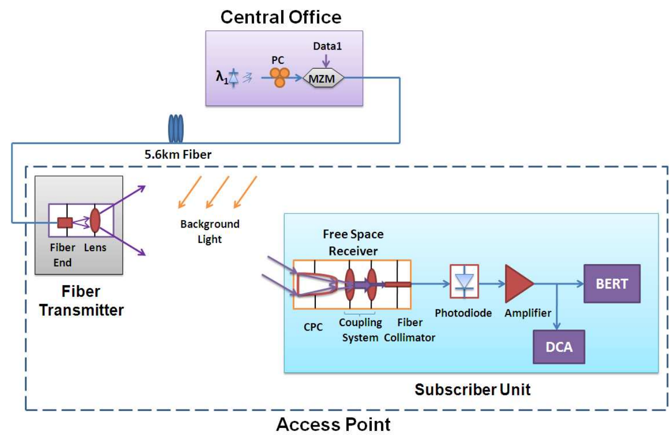


Fig. 2. Experimental setup.

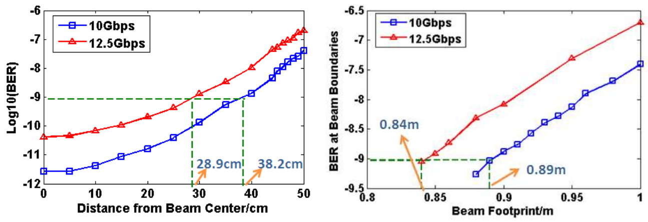
In real scenarios the subscriber maybe constantly moving inside the room, therefore the distance between the beam center and the subscriber is always varying and the signal light will enter the CPC with different incident angles. To quantify this we investigate and characterize the light properties at different distances from the beam center. Since the light coupling configuration in the receiver is sensitive to any tiny movement, the characterization and quantification are realized by tilting the transmitter horizontally.

The received signals with respect to different distances from beam center are shown in Fig. 3(a). In all the measurements we fix the beam footprint at the receiver to be 1m and the transmission power to be 7mW, which is the maximum allowable power according to the laser eye and skin safety regulations [14]. We have changed the distance between the fiber transmitter and the receiver from 0.65m to 2.5m while keeping the beam footprint constant at the receiver end and little difference in BER performance has been observed. The bit rates in the experiment are 10Gbps and 12.5Gbps respectively. It is obvious that for both cases when the distance from beam center increases the BER increases as well. This is simply due to the larger signal power collected by the CPC for smaller distance from beam center while the noise power remains almost constant. At the beam boundaries, a BER of $10^{-7.4}$ for the 10Gbps system and $10^{-6.7}$ for the 12.5Gbps system is achieved. If we define an error-free operation as a BER<10^{-9}, then error-free operation can be achieved when the distance from beam center is smaller than 28.9cm and 38.2cm respectively.

To achieve error-free operation over the entire footprint of

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.

the signal beam, we measured the BER at beam boundaries for different beam footprints since the BER there is the highest. The results are shown in Fig. 3(b). The bit rates investigated are 10Gbps and 12.5Gbps respectively and the transmission power is still fixed at 7mW. It is clear that the maximum beam footprints for 10Gbps and 12.5Gbps systems are 0.89m and 0.84m respectively. Inside this area, error-free reception can always be achieved. When the user moves out of this footprint which can be detected by our localization system, the steering mirror will guide the signal beam to the new position. As a result, error-free high-speed optical wireless communication with mobility feature can be achieved over the entire room.



(a) (b)

Fig. 3(a). BER with respect to distance from beam center and (b). BER at beam boundaries for different beam footprints.

From our investigation, it is obvious that there is a tradeoff between the bit rate and the size of error-free region. To further study this tradeoff, we also measured the maximum possible beam footprint when the system is operating at other bit rates. The results are shown in Fig. 4. The bit rate was varied from 1Gbps to 12.5Gbps. When the bit rate is 1Gbps, error-free reception can be achieved over an entire footprint of 2m. This result indicates that over the bit rate range of 1Gbps to 12.5Gbps, error-free operation can always be achieved with different maximum beam footprints. Therefore, different beam footprints and bit rates can be selected according to the system requirement. In addition, if error correction coding (ECC) is incorporated then the error-free threshold can be relaxed to BER<10^{-6}. The maximum beam footprints for different bit rates under this condition are also shown in Fig. 4. It can be seen that when the bit rate is 12.5Gbps, the beam footprint can be larger than 1m.

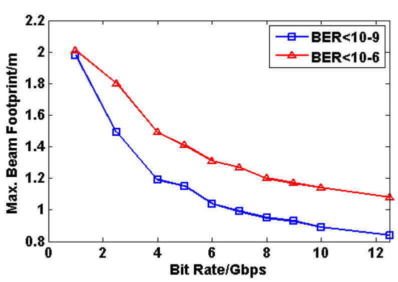


Fig. 4. Maximum beam footprint for different bit rates.

Although the system discussed here is only for down-stream communication, we have proposed the up-stream system in [10] for full-duplex operation and it has been verified with simulation. The experimental demonstration is in the progress. In addition, the integration of our system and the multiple users' situation are important issues that require careful consideration. The steering mirror in the fiber transmitter can be realized with MEMS and an array of them can be easily integrated together. Therefore, our system can then support multiple users when they are not within the same footprint either through time division multiplexing or wavelength division multiplexing.

IV. Conclusion

We proposed and demonstrated a 12.5Gbps optical wireless communication system with limited mobility and error-free reception within a footprint of 0.84m. If ECC is employed, this region can be extended to more than 1m. When this system is integrated with WiFi-based localization system, high-speed error-free wireless communication with mobility feature can be provided over the entire room.

We have also quantified the tradeoff between the beam footprint and bit rate and showed that there is a maximum beam footprint associated with each of the bit rates investigated for error-free reception. Therefore the bit rate and associated beam footprint can be chosen accordingly based on system requirements.

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