Efficient signalling technique for free space optics using auto-correlation OFDM

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***Abstract*— This document develops auto-correlated optical OFDM as a frame- work to implement OFDM on optical intensity channels. The drawbacks of conventional methods are mitigated in auto-correlated optical OFDM. Contrary to ACO-OFDM and DC-biased OFDM, the proposed technique uses all the available bandwidth for data modulation and does not require reserved subcarriers. Simulation results verify that auto-correlated optical OFDM has gain in Bit Error Rate as compared to conventional optical OFDM schemes.**

***Keywords*—, VCC, OFDM, VLC.**

1. Introduction

Wireless optical technology provides various outdoor and indoor services such as indoor wireless infrared communications, terrestrial links , wireless ultraviolet communications , and Free Space Optics . The latter case uses visible light (wavelengths of 380-750 nanometres) as the medium for data transmissions. In this case, an additional advantage lies in the potential for simultaneous use of light for illumination and data communication termed Free Space Optics (FSO).

Solid state lighting (SSL) refers to a type of lighting that uses semiconductor light emitting diodes (LEDs) as a source of illumination rather than electrical filaments (used in incandescent halogen light bulbs) or plasma (used in fluorescent lamps). Recent developments in LED technology are paving the way towards its full adoption as a replacement to incandescent and fluorescent lighting and white LEDs are now considered as future lighting solutions. Sales of inefficient incandescent light bulbs will be outlawed in Ontario and California beginning in 2012. Australia has announced a similar ban beginning in 2010 and inefficient incandescent bulbs are no longer in Europe as of 2009. Surveys compare LEDs versus incandescent light bulbs and fluorescent lamps in terms of lifetime, efficiency, reliability and cost. One of the main advantages of LEDs over other lighting methods is their longer lifetime expectancy. The average life span of an LED is about 60 kilo hours which is considerably more than average lifetime expectancy of incandescent bulbs (about 1200 hours)

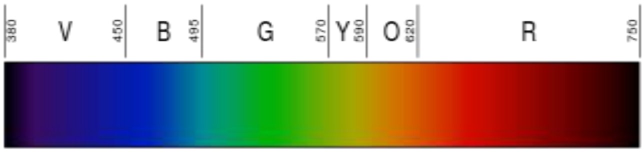

Figure 1.1: The visible spectrum corresponding to: 380-450 nm violet, 450-495 nm blue, 495-570 nm green, 570-590 nm yellow, 590-620 nm orange, and 620-750 nm red regionAnd fluorescent lamps (about 10 kilo hours). Other than that, LEDs are considered more energy efficient as they only consume about 6 W, which is 10% of the power used by incandescent bulbs (about 60 W), and 40% of that used by fluorescent lamps (about 14 W) per unit of light generated (lumen [lm]).Although the cost of a single LED bulb is more than an incandescent bulb or a fluorescent lamp (approximately $16 for LEDs made by STARLIGHT INC. compared to $1.25 and $3 for incandescent and fluorescents respectively), the total cost of employing LEDs in terms of operating hours and installations is much less than employing other two methods. For example, if the electricity cost is estimated about $0.2 per kWh, the total cost of employing LEDs for 60 kilo hours operation is estimated around $88 which is considerably less than that for incandescent lights ($783) and fluorescent lamps ($186) . As a result, LEDs are more economical for lighting purposes.
Fluorescent lamps contain toxic mercury that can be released if broken. Both incandescent light bulbs and fluorescent lamps suffer from their sensitivity to low temperatures and humid weathers. Hence, LEDs have less environmental impact and higher reliability in comparison to incandescent bulbs and fluorescents. However, the efficiency with which LEDs produce light degrades with heating effects. Further-more, the LEDs' brightness is limited per LED and sufficient number of LEDs is required for brightness of the area.
Apart from lighting advantages, LEDs can be modulated at rates greater than several hundred thousand times that of incandescent or fluorescent sources and hence offer the potential for data communication concurrent with lighting

1.1 Current State of FSO, Standardizations and Challenges

Visible light communications was pioneered in Japan but there is now a growing interest in Europe, namely the home Gigabit Access (OMEGA) project , and USA , namely

Boston Smart Lighting Centre. In order to have widespread adoption, FSO technology must be standardized. Today, there exist several Japanese standards such as Japan Electronics and Information Technology Industries Association (JEITA). The first standard JEITA CP-1221 restricts the wavelength of all emissions to be within the range of 380 nm to 750 nm with an accuracy of 1 nm per application. For example, if an application claims to send light within 450 nm to 500 nm, emitted wavelengths must be between 449 nm to 501 nm. Unlike this standard, JEITA CP-1222 is supposed to be only used for communications. It includes some restrictions in the frequency used and modulation schemes. There is also an ongoing work to develop FSO standards Within IEEE (IEEE 802.15). The IEEE has formed a task group 7 (TG7) which specifies and registers the required standards for FSO.

Similar to other wireless optical communication systems, FSO is aimed to allow high data rate communication between users. As an example, project OMEGA was intended to deliver 100+ Megabit/second (Mbit/s) data rate via interior lighting. However, as detailed in Sec. 2.1.4, the low modulation bandwidth of the LED, namely ~ 2 megahertz (MHz) for white LEDs restricts data rate. In terms of signal to Noise ratio (SNR), Free Space Optics systems possess high SNRs. SNRs in excess of 50 dB are available for typical FSO channels. In summary, the FSO channel can be characterized as low bandwidth with very high SNR. Therefore, there are several different techniques that can be employed to achieve higher data rates.

1.1.1 Methods to improve the data rate

As stated earlier, the modulation bandwidth of the LED is limited. As an example, the modulation bandwidth of a phosphor-based white LED is limited to ∼ 2 MHz to mitigate this effect; a common method is to employ optical filtering discussed in Sec. 2.1.5. For white LEDs, for example, detecting only the blue component of the emission enhances the modulation bandwidth to ∼ 20 MHz, albeit at the expense of some reduction in the received power.

Other than optical filtering, the work suggests transmitter equalization as a technique to increase FSO data rate. In that scenario, an array of LEDs with different peak frequencies are used to create a channel that has an improvement of a factor of 10 in the bandwidth. Using this method, a 2 meter (m) distance is covered with 40 Mbit/s non-return-to zero on-off keying (NRZ OOK) and a bit error rate (BER) of less than 10^{-6}. Mixing this technique and blue filtering at the receiver, an 80 Mbit/s link with the same BER is reported for the same distance coverage.

As another alternative, orthogonal frequency division multiplexing (OFDM), detailed in Sec. 2.2.1, is suggested. Through simultaneous transmission of lower data rates on parallel subcarriers instead of a high rate serial data, it is shown that OFDM has the capability to achieve higher data rates while each subcarrier is operating within a narrow band. Using blue filtering, reports 125 Mbit/s data rate over 5 m distance with NRZ OOK modulation and encoded BER of less than 2×10^{-3}. For the same BER, data rates of more than 200 Mbit/s are achieved using OFDM.

1.1.2 FSO Challenges

Although the discussed methods enhance the communication data rates, still very high data rates (more than a Gbit/s) are unachievable even with optical filtering and equalization techniques.

Apart from the challenge of achieving higher data rates, there are additional challenges for FSO. As discussed, providing a high speed FSO uplink is difficult. A reflecting transceiver is proposed. The reflector receives the incident light and returns a portion of the beam to the transmitter. However, the data rates achieved from this method are low (less than 50 Mbit/s).

Another challenge for FSO is to cooperate with another wireless standard such as RF. A work examined the combination of a high speed downlink and a lower speed RF wireless LAN and showed that the combined system possess some benefits in terms of latency and throughput. Also the work in OMEGA project aims to combine different RF and optical wireless to achieve the desired performance.

1.2 FSO Applications

The applications of FSO are not restricted to indoor uses. Some main applications of FSO are detailed in the following.

- Vehicle and transportation:

White LEDs can also be used in the automotive field to communicate audio or digital data between cars, between traffic infrastructure and cars, between robots or even between aircraft. The first cars that employ LEDs as headlights are now appearing. Figure 1.2 displays Free Space Optics between head and tail lights of two cars.

- Hospitals and healthcare:

Visible light is well-suited for communication in hospitals and healthcare, especially around MRI scanners and in operating theatres where RF radiations are undesirable. There is an ongoing project in Japan that is intended to incorporate FSO applications to hospitals and healthcare.

- Hazardous environments:

Free Space Optics is an attractive choice for areas where there is a risk of explosions (such as mines, petro-chemical plants, oil rigs etc.) as it provides both safe illumination and communications.

- Location based services:

There exist some applications for FSO that enable estimation of user location. The geospatial information authority (GSI) in Japan has already started the activity of indoor location estimation using white LEDs.

- Defence and security services:

Visible light is a strong candidate for new defense and security systems. The fact that visible light cannot be detected on the other side of a wall has considerable security advantages.

- Aviation:

Light emitting diodes are already used in aircraft for illumination and can also be employed to provide media services to passengers. Such application reduces the aircraft cost and weight since there is no need of wires.

- Underwater communications:

Visible light is very attractive for environments where radio waves do not propagate for a long distance. Since radio waves do not travel well through thick electrical conductors like water, FSO can be used as an alternative to support underwater communications. Such advancement can enable underwater vehicles and divers to communicate to each other. A work uses green light for underwater communications of up to 30 meter distance.

The applications discussed in this section focus on the use of visible light for illumination and data communication, with illumination as the main function. However, there exist some FSO applications in which illumination is not important. The experimental link proposed in this work uses visible red light lasers (650 nm red beam) for free-space optical communications to cover a range of 300 m at a potential data rate of 100 Mbit/s.

I. Conclusions

In this thesis, efficient OFDM signalling schemes for FSO systems are proposed. As shown in Sec. 2.5.1, DC-biased OFDM and asymmetrically clipped optical OFDM (ACO-OFDM) are examples of IM/DD compatible OFDM schemes. However, as it will also be detailed in Chapter 2, they have several drawbacks. In general, DC-biased OFDM signals suffer from poor average optical efficiency. Clipped multi-carrier systems such as ACO-OFDM provide better optical power efficiency compared to DC-biased OFDM. However, this is achieved at the expense of losing half the degrees of freedom and requiring higher PAPR compared to DC- biased OFDM.

In this thesis, a novel bandwidth efficient method to implement OFDM on IM/DD channels is presented and termed auto-correlated optical OFDM. The loss of half the degrees of freedom and high PAPR in ACO-OFDM is mitigated in auto-correlated optical OFDM. The proposed technique achieves gain both in average required transmitted power and PAPR compared to previous approaches.

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