Chapter 1

Introduction

1.1 Motivation

The demand for wireless capacity to access the Internet has greatly increased with rise in use of mobile computing devices including, laptops, tablets, and phones. We are increasingly using the Internet to access articles, financial services, social networking, shopping, multimedia applications, gaming etc to name a few. There is ongoing research and increasing commercial activity in the field of smart spaces where every-

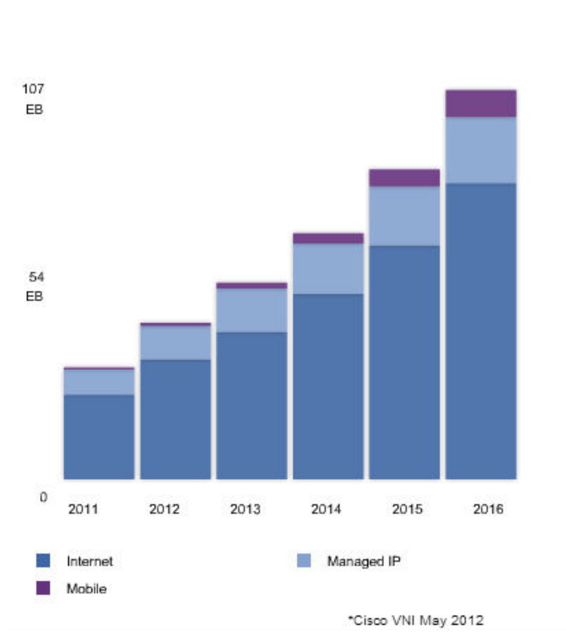

Figure 1·1: Cisco VNI Forecast

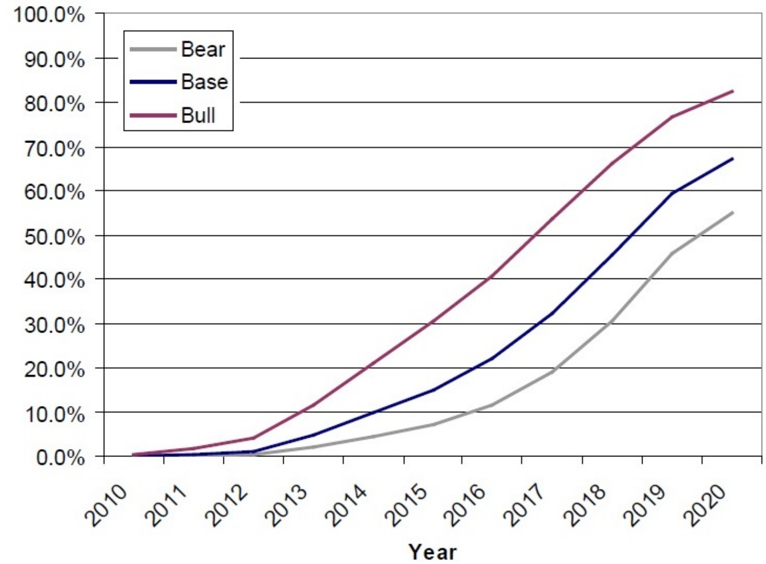

Figure 1·2: Total Cumulative Worldwide Socket Penetration

thing from appliances, gadgets, power grid to home security are networked via cloud based services. The Cisco VNI forecast illustrated in Figure 1·1 predicts this potential increase in networked traffic from current estimates of 54 EB to nearly double to 107 EB by 2016,

With increase in use of mobile devices to access online services, wireless is increasingly the preferred method for internet access. This is currently being accomplished using the electromagnetic radiation within the RF spectrum. The RF bandwidth is a limited resource and the existing spectral allocations limit the ability to increase its capacity thus making it ever so difficult to keep up with the wireless demand. In contrast to RF, light-based communication, and particularly the visible spectrum, is underutilized and has the potential to be exploited to provide extra capacity to meet the demand for wireless communications especially for indoor spaces.

Advances in solid state lighting has revolutionized the lighting industry. The realized energy and cost savings are leading the adoption of LEDs as the preferred source of illumination. Figure 1·2 (Baribeau, 2011) predicts a worldwide socket penetration of atleast 55% by year 2020. The output luminous flux from an LED varies proportional to the current through the device. Information trasmission can be achieved by modulating the current at a relatively high frequency ($>$ 200 Hz), generating a corresponding luminous flux, whose fluctuations are imperceptible to human eye. An optical receiver can sense this fluctuating illumination pattern and extract the transmitted information.

Under this model, each light in an indoor space can be deployed as a wireless access point while providing illumination. Directionality of light provides an extra layer of security. Deploying multiple devices within the indoor space enables spatial reuse over non-overlapping cones of illumination.

1.2 Coordinate Systems

Figure 1·3 illustrates coordinate systems used in the analysis. [$\hat{\mathbf{X}}$ $\hat{\mathbf{Y}}$ $\hat{\mathbf{Z}}$] and [$\hat{\mathbf{x}}$ $\hat{\mathbf{y}}$ $\hat{\mathbf{z}}$] are the basis vectors for the GCS and the RCS. A corner of the room is the origin of the

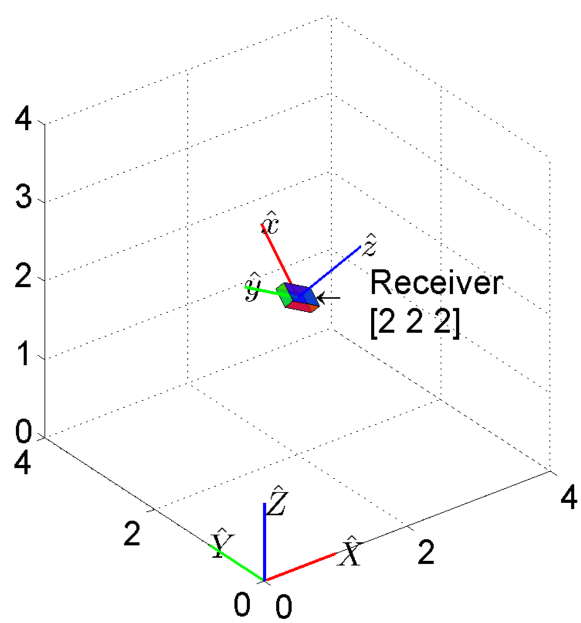

Figure 1·3: Illustration of the coordinate systems used

GCS while the center of the aperture of the receiver is set as the origin of RCS. The receiver's basis vectors are assumed always parallel to the length, width and surface normal of the sensor.

Let $[x_{tx}\ y_{tx}\ z_{tx}]$ be the location of centroid (C_{tx}) of the illumination surface of the transmitter and $[x_{rx}\ y_{rx}\ z_{rx}]$ be the location of the centroid of the receiver concentrator surface in the GCS. The optical axis is then defined by $\mathbf{d}$ and the vertical distance between the transmitter and receiver is given by $\mathbf{d^z}$.

$$\mathbf{d} = \begin{bmatrix} x_{tx} \\ y_{tx} \\ z_{tx} \end{bmatrix} - \begin{bmatrix} x_{rx} \\ y_{rx} \\ z_{rx} \end{bmatrix} \tag{1.1}$$

$$\mathbf{d^z} = (\mathbf{d}.\hat{\mathbf{z}})\hat{\mathbf{z}} \tag{1.2}$$

1.3 System Outline

The communication system under the VLC model operates under the hybrid wireless model paradigm using the VLC channel as the high capacity downlink and another medium for the uplink. This seems to be the accepted model and a reasonable assumption (Rahaim et al., 2011). Figure 1·4 illustrates a block diagram for a typical VLC downlink.

1.3.1 Data Source

The source is an entity that, while performing its tasks, produces information that needs to be communicated to another entity.

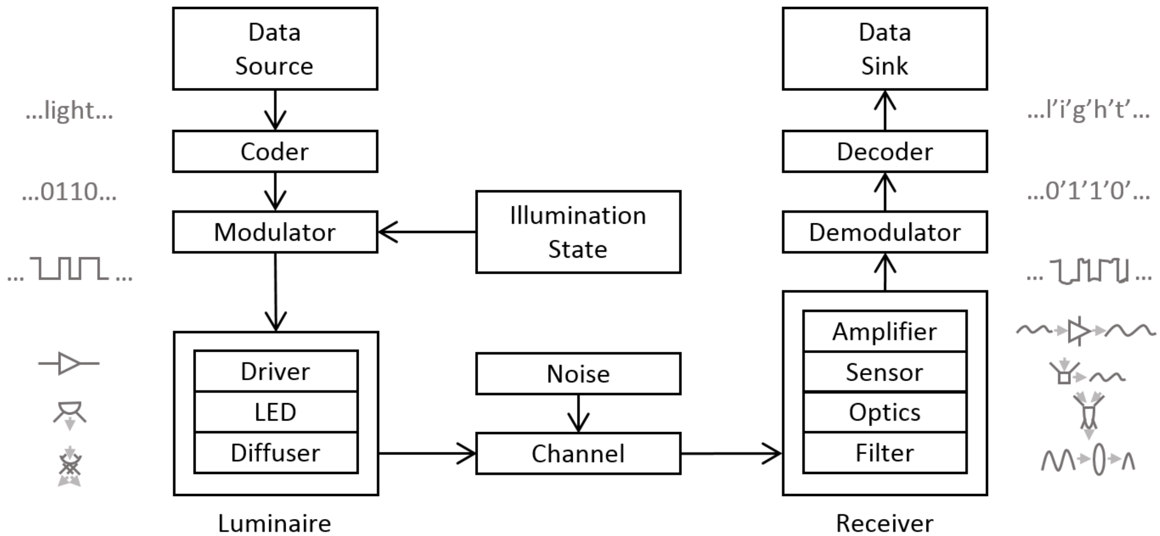

Figure 1·4: VLC downlink block diagram

1.3.2 Coder

The coder converts data from the source to a binary bit sequence. In this process, it may introduce redudancy to reduce the effect of noise and interference in the channel.

1.3.3 Illumination State

The illumination state sets the average output flux and the SPD to be produced by each luminaire. This is a result of a number of factors such as (a) requested illumination level by person in the space (b) optimal energy usage (c) output of 'smart' applications such as circadian control, etc...

1.3.4 Modulator

The modulator, with the knowledge of requested flux, converts the bit sequence into a corresponding waveform that drives the luminaire. The frequency of visible light is in the range of about 400-800 THz. The current state-of-art electronics cannot sample and process signals at that high speeds. Thus traditional modulation schemes which vary the amplitude, frequency or phase of the waveforms withinin the RF spectrum cannot be directly implemented within the visible spectrum. Instead, the average power (a.k.a flux/intensity) of the visible waveforms are modulated to transmit data. Optical sensors like PDs produce output current proportional to the intensity of the incident radiation and not the waveform of the radiation itself. This signalling scheme is known as IM/DD.

1.3.5 Luminaire

The luminaire is composed of driver, LED(s) and diffuser. A simple LED driver is a transconductance amplifier whose input is the waveform produced by the modulator. The corresponding output current drives the LED which in turn generates light.

A luminaire is made up of number of phosphor converted white LEDs or different narrow-band devices which produce diferent colors. A phosphor converted white LED is made by coating a blue LED with yellow phosphor. The blue light excites the yellow phosphor and together they produce white light.

The diffuser scatters the light produced by the LED(s) to mix the different colors. It also makes the luminous surface appear softer and more pleasing to the eye. Different diffuser front ends generate different sizes of cones of emission. The most common emission pattern is the lambertian pattern. Let ϕ be the angle subtended between the transmitter surface normal and direction of emission, $\phi_{1/2}$ be the transmitter semi-angle and m be the order of emission. Then Eq.1.3a defines the lambertian radiant intensity at any angle ϕ.

$$L(\phi) = \begin{cases} \frac{(m+1)}{2\pi} cos^m(\phi) & ; -\pi/2 \leq \phi \leq \pi/2 \\ 0 & ;\ \text{else} \end{cases} \tag{1.3a}$$

$$m = -\frac{\ln(2)}{\cos(\phi_{1/2})} \tag{1.3b}$$

1.3.6 Channel

The channel is the medium through which information flows. It is made up of all the paths travelled by the light rays between the luminaire and the receiver. Depending on the number of transmitters, colors or number of receiving elements, the channel can be configured into a various single/multiple input single/multiple output configurations.

1.3.7 Receiver

A receiver is made up of an optical filter, optics, an optical sensor like PD (PIN or APD) and a TIA. Some high speed systems transmit data over a small range of wavelengths (ex Blue (400-500nm)) while the entire visible spectrum is used for illumination. In such cases, a blue filter is used to remove noise from parts of the optical spectrum that do not carry any data. For WDM systems where data is transmitted independently over different parts of the spectrum, multiple non-overlapping filters are used to decorrelate the different streams of information. For single pixel receivers, concentrator optics are used to increase the effective area of the sensor while keeping its capacitance at a minimum. A number of single pixel receivers can be configured in a matrix pattern to realize a non-imaging multiple element receiver. For imaging receivers, imaging optics are used to help decorrelate the multiple channels. Noise introduced by the channel distorts the signal waveform.

1.3.8 Demodulator

The demodulator, with prior knowledge of the modulation scheme implemented, tries recreate the transmitted bit sequence from the received waveform. Significant noise that is not orthogonal to the signal waveform can introduce errors in the demodulated sequence.

1.3.9 Decoder

The decoder, with prior knowledge of the coding scheme implemented, tries to recover the transmitted data from the bit stream. Redundancy itroduced in the coded data can help the decoder to detect and rectify errors.

1.3.10 Data Sink

Ideally, the data sink is the entity to which the information was transmitted to.

1.4 Related work

1.4.1 LED Bandwidth

At conventional office lighting illumination levels (400 lux), a single-input single-output (SISO) optical communication channel operates at a high signal to noise ratio (SNR) but is limited in its capacity due to the inherent low switching speeds of high brightness LEDs used for illumination (1-2 MHz). In a phosphor converted white LED, while the blue LED can be modulated at higher frequencies, the phosphor conversion procecess is a relatively slow process thus limiting the bandwidth of the LED. (Grubor et al., 2008) used a blue filter at the receiver to extract just the blue part of the incident spectrum and thus improve the modulation 3dB bandwidth of the LED to about 20 MHz; however at the cost of the received signal power. In (Minh et al., 2008), the authors use resonance equalization at the transmitter to achieve an overall 3dB bandwidth of about 25 MHz. In (Zeng et al., 2008), the authors use an equilizer at the receiver to extend the channel 3dB bandwidth to about 50 MHz.

1.4.2 Spectral Efficiency

Another way to increase the datarate of a SISO link is to improve the spectral efficiency of the channel. For this, spectrally efficient complex modulation schemes like OFDM or DMT implemented in the RF domain have been modified to meet the optical constraints (Vucic et al., 2009; Mesleh et al., 2010b; Mesleh et al., 2010a; Dissanayake et al., 2011). In DCO-OFDM (MSM) (Carruthers and Kahn, 1996), a DC bias is added to a real valued time domain OFDM symbol to minimize signal clipping. While this technique does increase the spectral efficiency, it is power inefficient. In ACO-OFDM (Armstrong and Lowery, 2006), half the spectral efficiency of DCO-OFDM is sacrificed for power efficiency. In this technique, data is assigned to only the odd subcarriers and the time domain OFDM symbol is clipped below 0. Noise introduced due to clipping in this manner has been shown to be orthogonal to the signal. The entire symbol (with additive noise) can be reconstructed at the receiver and transmitted data can be recovered.

1.4.3 Experimental Implementations

In (Vucic et al., 2010), the authors experimentally achieve 513 Mbps data rates over a SISO link for BER $\leq 2 \times 10^{-3}$. The transmitter implemented DMT with 127 subcarriers within a bandwidth of 100 MHz (beyond the 3dB bandwidth); each moduated with different M-QAM constellation based on bit and power loading. An equalizer was implemented at the receiver based on the estimated channel. The system was operated at 1000 lx illumination at the receiver.

In (Cossu et al., 2012), the authors experimentally achieve 1.5 Gbps for a SISO link and 3.4 Gbps data rates over a WDM MIMO link for BER $\leq 2 * 10^{-3}$ using commercial RGB LED. In both cases, the transmitter implemented DMT with 512 subcarriers within a bandwidth of 250 MHz; each moduated with different M-QAM constellation based on bit and power loading. An equalizer was implemented at the receiver based on the estimated channel. The system was operated at 410 lx illumination at the receiver.

For SM, a non-imaging receiver suffers from outages at symmetry points. At the same time the channel matrix is ill-conditioned (Zeng et al., 2009). While coverage can be improved using angle diversity receivers (Carruthers and Kahn, 2000), the performance can be enhanced remarkably by considering an imaging receiver to decorrelate the coefficients of the MIMO channel matrix (Djahani and Kahn, 2000). The imaging receiver architecture (Kahn et al., 1998) has the potential to provide the highest capacity for a VLC channel along being incorporated in a handheld device.

A spatial multiplexing indoor MIMO technique for VLC technology using OFDM and a imaging receiver is considered in (Azhar et al., 2013). Here a 4x9 MIMO system is implemented. Here, the four transmitters implement DCO-OFDM with 32 subcarriers within a bandwidth of 4 MHz; each modulated with M-QAM symbols. Blue filtering and equalization is implemented at the receiver. The authors experimentally achieve 1 Gbps tramsmission with average BER $\leq 10^{-3}$ at an illumination of 1000 lx.

1.4.4 IEEE 802.15 Task Group 7

The IEEE 802.15.7 task group has drafted MAC and PHY standards to support free space optical communications. These specifications enable high data rate communications along with dimming. The current LED infrastructure can support the PHYIII specifications (Rajagopal et al., 2012). The proposed modulation scheme is CSK. In CSK, bits are encoded in the color that the luminaire produces. To transmit a bit sequence, the luminaire produces different colors which are averaged out by the human eye to produce the 'white' set point. The standard supports 16-CSK at 24 MHz clock rate which can provide data rates upto 96 Mb/s.

Since the source data drives the luminaires to produce different colors, data dependent color shift is an inherent issue within CSK. Metameric modulation (Butala et al., 2012) is a scheme that mitigates this issue while achieving the same spectral efficiency as CSK.

1.5 Summary of Accomplishments

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