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 everything from appliances, gadgets, power grid to home security are networked via cloud based services. These devices have been widely adopted and have become an integral part of our daily lives. The Cisco VNI forecast illustrated in Figure 1·1 predicts increase in networked traffic at a cumulative rate of 61% per year – thus network traffic shall double every two years.

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 radio frequency (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, unregulated and has the potential to be exploited to provide extra capacity to meet the demand for wireless communications especially

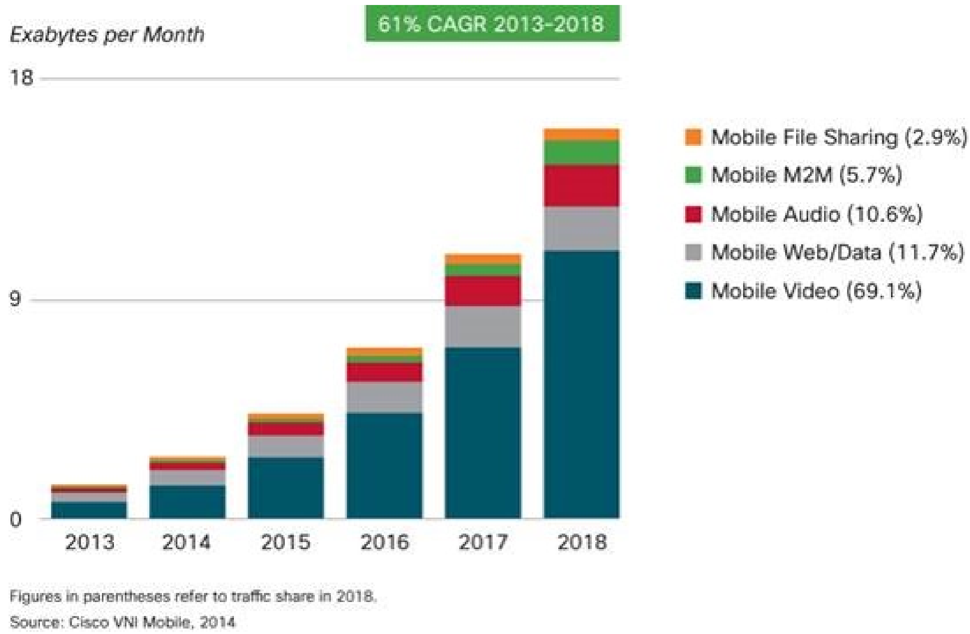

Figure 1·1: Cisco VNI forecast

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 at least 55% by year 2020. Lighting companies are now competing to replace all existing lighting with the new energy–efficient LED devices. Because lighting is well positioned to support human activities, it is also well positioned to serve as a highly localized wireless access vehicle by modulating the visible spectrum (380 nm – 780 nm). This model is called the 'dual use' of lighting and communication. In a practical implementation, overhead luminaires provide light and data downlink as an offload medium, being augmented by the availability of other media including RF as part of a heterogeneous network (Gancarz et al., 2013; Rahaim and Little, 2015).

The output luminous flux from an LED varies proportional to the current through the device. Information transmission can be achieved by modulating the current at a

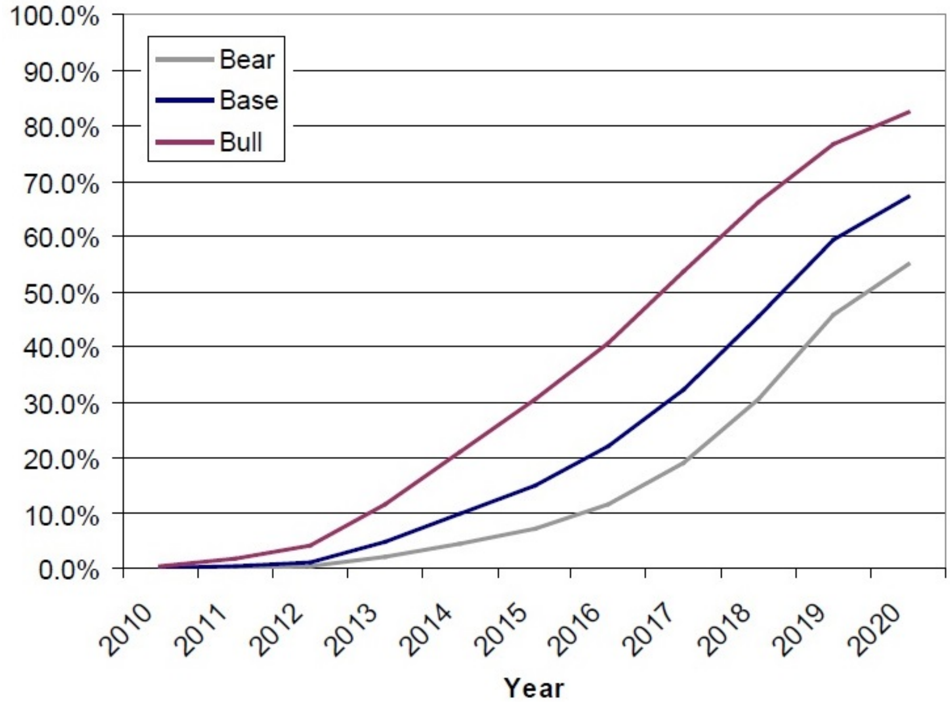

Figure 1·2: Total cumulative worldwide socket penetration

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. This form of information transfer is known as intensity modulation / direct detection (IM/DD) and is widely used for optical wireless communications (OWC). Under this model, each light in an indoor space can be deployed as a wireless access point while providing illumination. Directionality of light along with high attenuation while propagating through walls provides an extra layer of security for information exchange with light in indoor spaces. Deploying multiple devices within the indoor space enables spatial reuse over non-overlapping cones of illumination thus providing high bandwidth density.

1.2 The optical downlink

1.2.1 Common terminology

This sub–section outlines optical terminology used in the rest of the text.

Radiant flux

Radiant flux is the amount of radiant energy emitted per unit time by an optical source. Let $P(\lambda)$ be the SPD under consideration. The radiant flux Φ_W corresponding to the SPD is given by

$$\Phi_{\mathrm{W}} = \int_{\lambda_{\min}}^{\lambda_{\max}} P(\lambda) d\lambda \tag{1.1}$$

(Units: W).

Radiant intensity

Radiant intensity is the amount of radiant flux emitted per unit solid angle by an optical source. (Units: W/sr)

Irradiance

Irradiance is the amount of radiant flux received by a surface/device per unit area. (Units: $\mathrm{W/m^2}$)

Luminous flux

Luminous flux is the amount of luminous energy emitted per unit time by an optical source. Let $P(\lambda)$ be the SPD under consideration. The luminous flux Φ_{lm}

corresponding to the SPD is given by (Grubor et al., 2008)

$$\Phi_{\mathrm{lm}} = 683 \int_{380\text{ nm}}^{780\text{ nm}} P(\lambda)V(\lambda)d\lambda \tag{1.2}$$

where $V(\lambda)$ is the eye sensitivity function. (Units: lm).

Luminous intensity

Luminous intensity is the amount of luminous flux emitted per unit solid angle by an optical source. (Units: lm/sr)

Illuminance

Illuminance is the amount of luminous flux received by a surface/device per unit area. (Units: lm/m^2)

1.2.2 The optical signal chain

A practical OWC system operates under the hybrid wireless model paradigm using the visible light communication (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 and Little, 2015). Figure 1·3 illustrates a block diagram for a typical downlink using the optical spectrum.

Data source

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

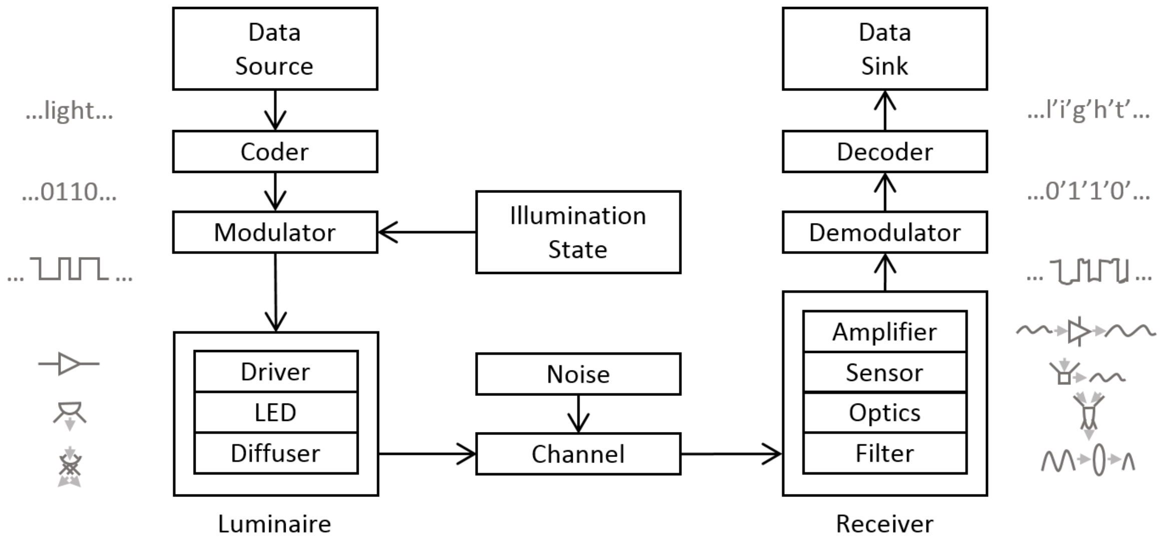

Figure 1·3: OWC downlink block diagram

Coder

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

Illumination state

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

Modulator

The modulator, with the knowledge of requested flux, maps and converts the bit sequence into a corresponding waveform that drives the luminaire. The frequency of visible light is in the range of about 380 THz – 780 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 within 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 photodiodes (PD) produce output current proportional to the intensity of the incident radiation and not the waveform of the radiation itself. This signaling scheme is known as IM/DD. All optical modulation techniques are implemented in conjunction with IM/DD. This method introduces unique constraints that differentiate optical modulation techniques from RF modulation techniques.

Luminaire/Transmitter

The luminaire is composed of a driver, LEDs and diffuser optics. A simple LED driver is a trans–conductance 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 different 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 and output a relatively homogenous, glare–free light which 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.

Channel

The channel is the medium through which information flows. It is made up of all the paths traveled 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. For the OWC downlink, the indoor space acts as the channel. In addition to the line-of-sight (LOS) path from the luminaire to the receiver, various reflected rays of light propagating over different path lengths may be incident on the receiver. In an RF system, such multi–paths cause inter-symbol-interference (ISI) that needs to be resolved for. In the indoor OWC system, due to poor reflectivity off various walls and directionality of receiving optics, optical signals propagating over such multi–paths have been shown to be heavily attenuated when incident on the active element of the receiver. In addition, difference in path lengths between LOS and non-LOS (NLOS) propagation within indoor spaces is very small. This produces a small delay spread which is insignificant when compared to frequency of intensity modulation.

Receiver

A receiver is made up of an optical filter, refractive optics, an optical sensor like PD and an amplifier. Some high speed systems transmit data over a small range of wavelengths (ex blue (400 nm – 500 nm)) 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 information. For wavelength division multiplexed (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. Sensor devices such as p-i-n junction photodiode (PIN-PD), avalanche photodiode (APD) or complementary metal oxide semiconductor (CMOS) active pixel devices generate an electrical signal proportional to radiant flux incident on the sensor. This electrical signal is amplified and conditioned before it is processed to recover transmitted information. Randomness in photon arrival and sensing gives rise to shot noise within the system. Amplifiers such as trans–impedance amplifiers (TIA) introduce thermal noise into the system. This noise then distorts the signal waveform and can cause errors in information recovery.

Demodulator

With prior knowledge of the modulation scheme implemented, the demodulator makes an intelligent estimate of the transmitted signal waveform. After recovering the transmitted waveform, it de–maps it to recover the transmitted bit sequence. Significant noise that is not orthogonal to the signal waveform can introduce errors in the demodulated sequence.

Decoder

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

Data sink

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

1.3 Related work

For OWC to be a viable candidate for mitigating 'bottleneck' on wireless downlink, the achievable data rates per user need to be at least of the same order as those using RF. Wireless data rates are directly proportional to a function of achievable bandwidth and spectral efficiency of modulation techniques. Research to improve the performance of OWC has gained traction in recent years. These have been focused on improving the achievable bandwidth using LEDs and spectral efficiency of employed modulation techniques. Along the way, a few experimental prototypes have also been reported.

1.3.1 Enhancing 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 MHz – 2 MHz). In a phosphor converted white LED, while the blue LED can be modulated at higher frequencies, the phosphor conversion process 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 3 dB 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 3 dB bandwidth of about 25 MHz. In (Zeng et al., 2008), the authors use an equalizer at the receiver to extend the channel 3 dB bandwidth to about 50 MHz. In (Tsonev et al., 2014), μLEDs have been shown to provide 3 dB bandwidth of 60 MHz. However, feasibility of μLEDs for illumination purposes is yet to be tested. The LED device itself has a slow roll–off in its frequency response beyond its 3 dB attenuation point. This makes it possible to transmit information at higher frequencies using lower order modulation techniques corresponding to lower achievable SNRs while maintaining a target bit error rate (BER).

1.3.2 Enhancing spectral efficiency

Another way to increase the datarate of OWC is to implement spectrally efficient modulation techniques. For this, orthogonal frequency division multiplexing (OFDM) or discrete multi–tone (DMT) modulation 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 (Carruthers and Kahn, 1996), a multiple subcarrier modulation (MSM) technique is implemented by adding DC bias to a real valued time domain OFDM symbol to minimize signal clipping. This technique is also known as DCO-OFDM. 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 zero. 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. Higher spectral efficiencies can be achieved by using multiple transmitting elements with multiple receiving elements in a multiple–input multiple–output (MIMO) system. Such a MIMO system can exploit additional dimensions of space and color. Spatial modulation (SM) (Mesleh et al., 2006) exploits the spatial dimension by encoding bits in the index of an active transmitter. Color shift keying (CSK) (IEEE 802.15.7, 2011) exploits the color dimension by encoding bits in the color of the transmitted flux.

1.3.3 Experimental prototypes

In (Vucic et al., 2010), the authors experimentally achieve 513 Mb/s 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 modulated with different M-ary quadrature amplitude modulation (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. (Tsonev et al., 2014) implement optical OFDM techniques with 512 subcarriers, pre–equalization and bit and power loading along with gallium nitride μLED front end to demonstrate feasibility of 3 Gb/s SISO link. In (Cossu et al., 2012), the authors experimentally achieve 1.5 Gb/s for a SISO link and 3.4 Gb/s data rates over a wavelength division multiplexed (WDM) MIMO link for BER $\leq 2 * 10^{-3}$ using commercial red, green and blue (RGB) LED. In both cases, the transmitter implemented DMT with 512 subcarriers within a bandwidth of 250 MHz; each modulated 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 Gb/s transmission with average BER $\leq 10^{-3}$ at an illumination of 1000 lx. Some research has been carried out to achieve low datarate optical communications using cameras in mobile devices. CamCom protocol (Roberts, 2013) is being developed by researchers at Intel to integrate OWC with existing portable devices equipped with cameras.

1.3.4 IEEE 802.15 task group 7

The IEEE 802.15.7 task group has drafted medium access control (MAC) and physical layer (PHY) standards to support free space optical communications (IEEE 802.15.7, 2011). These specifications enable high data rate communications along with dimming. The current LED infrastructure can support the PHYIII specifications (Rajagopal et al., 2012). The standard outlines CSK with a linear system model to implement OWC with PHY III. 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 up to 16-CSK at 24 MHz clock rate which can provide data rates up to 96 Mb/s.

1.4 Summary of accomplishments

This dissertation investigates modulation techniques in conjunction with IM/DD for indoor optical wireless broadcast systems in presence of user requested illumination targets. A framework is developed to analyze performance of imaging MIMO systems. Performance improvements for optical systems have been achieved by decorrelating spatially separate links by incorporating an imaging receiver. Sample indexed spatial orthogonal frequency division multiplexing (SIS-OFDM) - a novel MIMO modulation technique that exploits the spatial, temporal and frequency dimensions is introduced in order to achieve high spectral efficiency of a MIMO OWC system while maintaining relatively low system complexity. Human visual perception can be characterized by the *commission internationale de l'eclairage* (CIE) 1931 XYZ color space. Impact of non-linearity of this space on performance of CSK is then studied under a non-linear system model. Luminous-signal-to-noise ratio (LSNR), a metric to compare performance of different signaling techniques operating at same illumination intensity levels, is introduced. Metameric modulation (MM) is also introduced and studied as a MIMO signaling technique that exploits the color dimension with multiple sets of LEDs to improve spectral efficiency. The dissertation then introduces the singular value decomposition (SVD) based OWC system architecture to incorporate illumination constraints independent of communication constraints in a MIMO system. It then studies design paradigm for a multi–colored wavelength division multiplexed indoor OWC system.

As a part of the smart lighting engineering research center, during this dissertation, various prototypes and proof-of-concept demonstrations have been developed in collaboration with partners at Tufts University and Rensselaer Polytechnic Institute. Specifications were generated to develop a 4×4 optical MIMO system with an imaging receiver to operate it at 400 lx illumination level. A color sensor platform (CuSP) has also been developed to create a network of color sensor platforms in a smart space that support smart controls.

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