Li-Fi

A Critical Analysis in Technology, Business and Policy

Team 1

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Abstract

Li-Fi is an upcoming Visible Light Communication (VLC) technology in the world of Telecommunications that leverages Light-Emitting Diodes (LEDs) to provide high speed transmission. Li-Fi proposes a multi-point bi-directional communication system.

This technology has great potential so it is important to understand its technology characteristics and commercial capabilities. We delve into the technological aspect of Li-Fi including components, network infrastructure, modulation, security and reliability. In terms of business, we address value analysis, market demand, incumbents and SWOT analysis. In the policy aspect, we review the prevalent and proposed IEEE standards for Li-Fi.

Our analysis is followed by a case study using PureLiFi. We then explore the specific applications that can harness Li-Fi and subsequently the implications of using Li-Fi. Analysis of Li-Fi as a whole and comparison with technologies like Wi-Fi are also conducted. At the end of this report, we provide our proposal, recommendation and future scope of Li-Fi based on our study.

Keywords: Li-Fi (Light Fidelity), VLC (Visible Light Communication), IEEE, LED (Light Emitting Diode), Wi-Fi

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Chapter 1. What is Li-Fi?

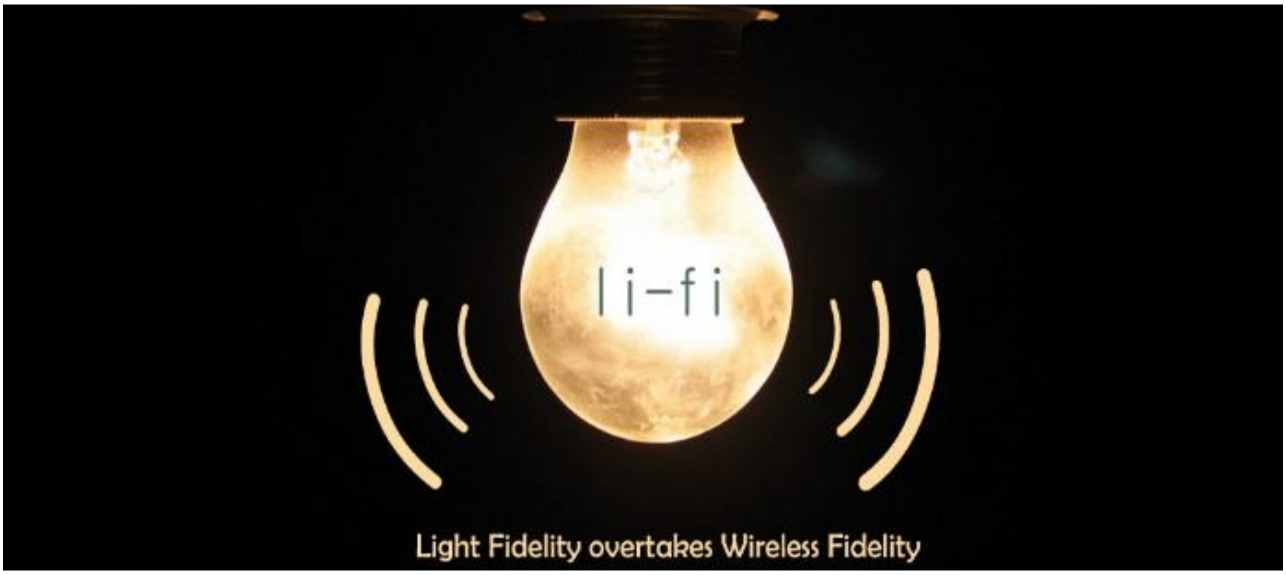
1.1 Introduction of Li-Fi

The surge in popularity of the Internet over the last couple of decades, has transpired into an ever increasing demand for communicating at high transmission speeds. With the evolution in access-internet technologies, Wi-Fi emerged as a breakthrough technology in the 90s. However, with the growth of the Internet all over the world, we are heading towards a potential radio spectrum crisis, which calls for alternate solutions which can harness the broader electromagnetic spectrum. Under such circumstances, Li-Fi is brought about as one of such technologies that is currently being explored to coexist with or complement Wi-Fi.

Li-Fi (or Light Fidelity) is a wireless communication technology that operates in the visible light spectrum. The technology is categorised under optical wireless communication since it uses the visible part of the electromagnetic spectrum i.e. 400 nm - 700 nm wavelengths. Li-Fi has garnered much interest due to the very high speed that it promises. So far it has achieved a transmission speed as fast as 224 Gigabits per second in the lab.

Li-Fi poses several advantages that require us to take a closer look at why it is important to pay attention to this in the coming years. It offers an environment friendly way of wireless communication. On the one hand, Li-Fi functions in the presence of any light source, strengthening its ubiquitous availability. On the other hand, it consumes less power and produces emission of heat.

We are exploring Li-Fi from a technology, business and policy standpoint to evaluate its pros and cons in order to perform an analysis on where Li-Fi can be leveraged best, what value it adds to wireless communication systems and whether it is here to stay.



Meet Wi-Fi's successor – Li-Fi, which is 100 times faster than Wi-Fi, 2015

1.2 History of Li-Fi

Li-Fi was started as part of the Visible Light Communications (VLC) project in the Nakagawa Laboratory in 2003 in Keio University, Japan where Light Emitting Diodes (LEDs) were first used to transmit data (*Visible light communication*, 2016). Professor Harald Haas coined the term Li-Fi at his TED talk in 2011. He explained the concept and possibility of using every light or LED out there for wireless data communications *(Haas, data, and bulb, 2016).* Professor Haas also established a company called PureLiFi to commercialise Li-Fi, which we discuss in the following sections. *(Haas, data, and bulb, 2016).*

Li-Fi stands out among most other VLC technologies due to its multi-point bidirectional nature. Professor Haas illustrated that implementing Li-Fi would take people closer by enabling each one of us to compute and communicate anywhere and at any instant due to the ubiquity of light producing devices.

Chapter 2. Technology Analysis

2.1 Li-Fi Components

Li-Fi has three components, shown as the chart below:

Network	FTTH (Fiber to the home)
Front End	LED (short distance) / laser (long distance)
Receiver End	Photo-detector (photodiode). E.g. solar panel

Components of Li-Fi Technology

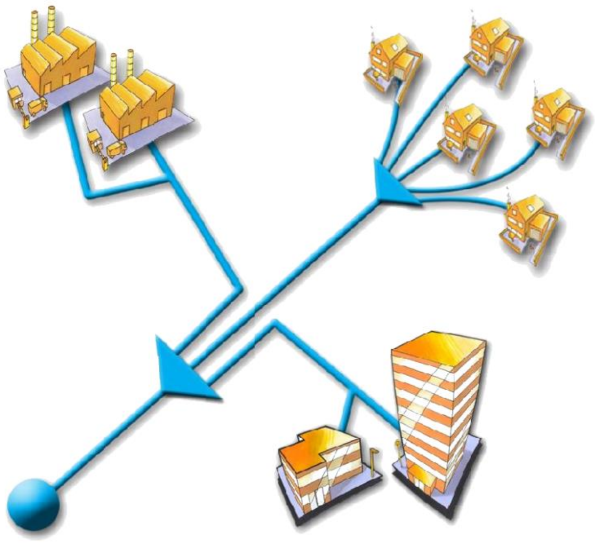
2.2 Network Infrastructure

Since Li-Fi will utilise LED lighting bulbs as the main signal transmitter and in order to guarantee the transmission rate, network stability and the transmission device number for each in-door Li-Fi network, we are proposing FTTH network as the basic network infrastructure for Li-Fi connection.

To build the most suitable architecture for different use cases of Li-Fi network, two general FTTH architectures described in Europe FTTH Council White Book *(Network Infrastructure Committee, 2007)* are taken into consideration:

- **PON Architecture**

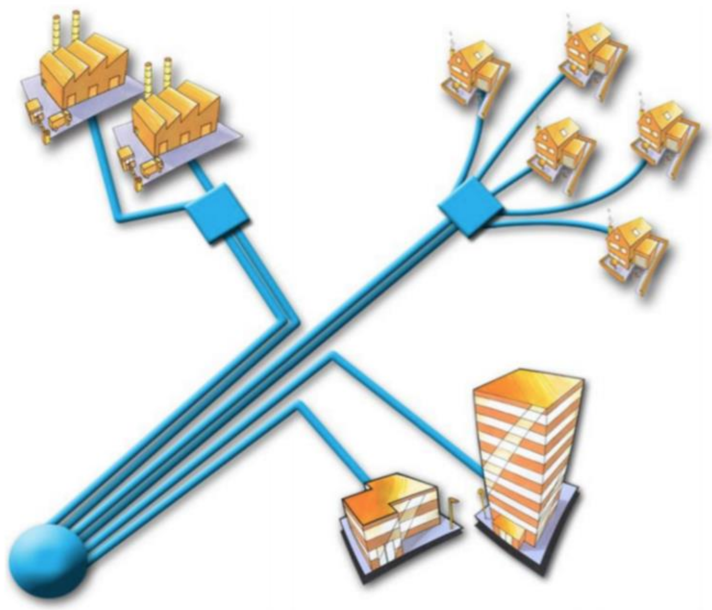
PON architecture consists of single optical driver with capability of 64 users (at most 128 users) and passive splitters which are placed in the access node near the user. The splitters divide the traffic to multiple users. This architecture is limited to the number of feeder cables that it can support.



PON Architecture (Network Infrastructure Committee, 2007)

- **P2P Architecture**

Unlike the PON architecture, the P2P architecture provides each user with a dedicated fiber connection from POP and therefore provides best ensure of network connection.



P2P Architecture (Network Infrastructure Committee, 2007)

Among the current networks, FTTH is the one that guarantees best data transmission rate. Other networks such as FTTN, FTTP and HFC are also using optical fiber as part of their network infrastructure. But end users will experience a lower transmission rate due to the bottleneck introduced by the copper wires or coaxial cables.

2.3 Transmission Process

Li-Fi achieves multiple user connection and data transmission by using Orthogonal Frequency Division Multiplexing (OFDM) to modulate the fluctuations in the intensity of light. This process can be divided into two parts, data transmission within network and data transmission in Li-Fi.

2.3.1 Data transmission within network

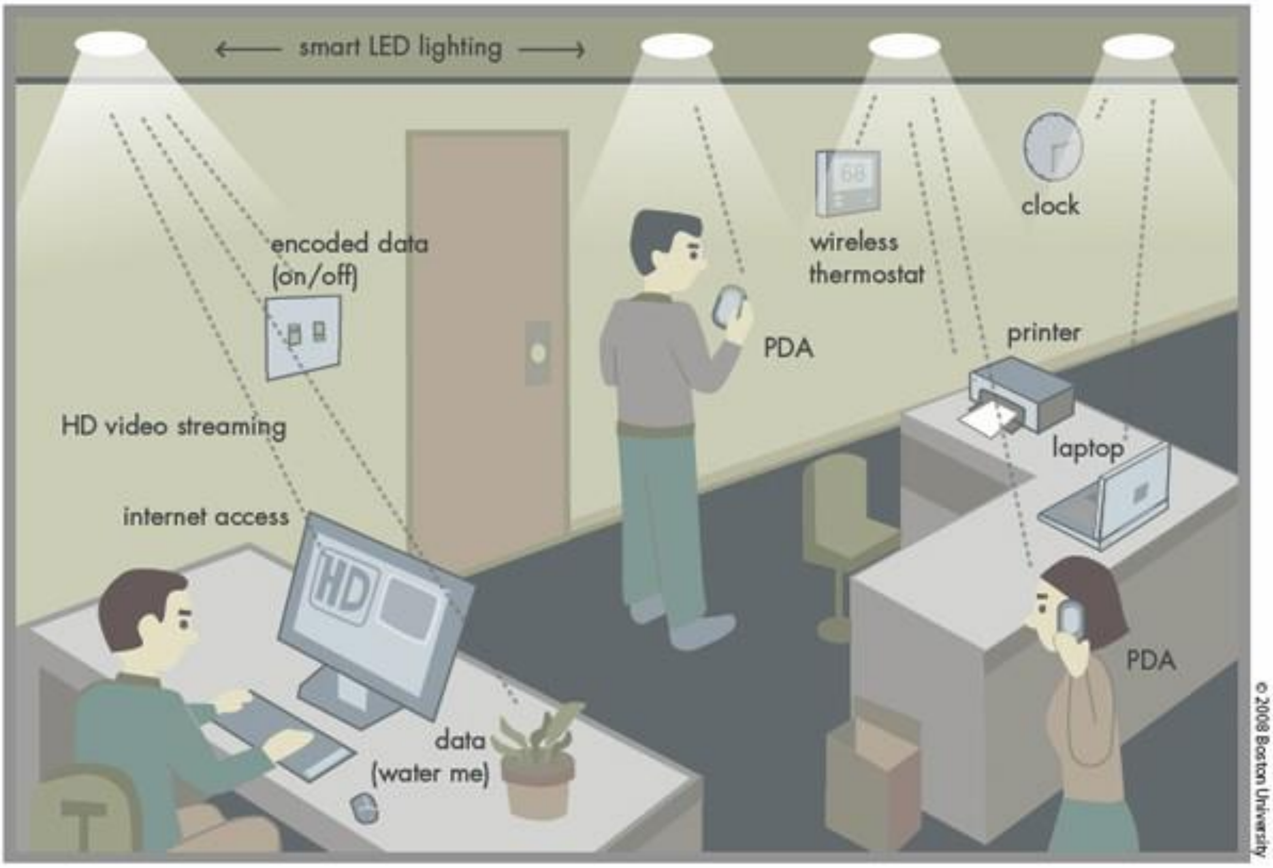
Through the higher level of FTTH network infrastructure that was proposed, data is transmitted in the same form as that of fibre optic communication. In other words, at the sender, electrical signals are converted into streams of lighting information, represented by the density of photons. Whereas at the receiver, light signals are detected by the photon detectors and converted back into electrical signals.

2.3.2 Data transmission in Li-Fi

Bit streams represented by a current are received by the signal processing unit located at the optical front-ends . A constant stream of photons is emitted by applying constant currents on the LED lighting bulb *(Anon, 2016)*. A variation of the current also impacts the intensity of light. Besides, according to the characteristic of LED lighting bulb, which is a type of semi-conductor, the information can be modulated very intensely. Before transmitting, electronic signals are converted into light signals (photons) by the transmitter chip located at the front end. During the conversion process, multi-carrier modulation is used to achieve multi-access characteristic.

One factor that enables Li-Fi to achieve high speed transmission is the large visible light bandwidth that it uses. In fact, the bandwidth of light is 10,000 times larger than that of radio communication, enabling the light to achieve extremely high transmission rate according to Shannon Theory. Combining the high fluctuation rate of light and the large bandwidth, data transmission rate can be achieved up to 224 gigabits per second *(Mercer, 2016)*.

The signals represented by the changes of lightness are then detected by photodiode (PD) located at the receiver end and converted back to different amplitudes of electrical current. The receiver chip, which is located between the network access point and the receiver end, demodulates the received electrical signals into binary data streams and then sends them to the user.



Li-Fi in home and offices (Crew, 2016)

2.3.3 Hybrid Li-Fi and Wi-Fi network

To address Li-Fi's capability to communicate both outdoor and indoor, a hybrid network model that integrates Li-Fi and Wi-Fi is proposed *(Haas et al., 2016)*. It's called Hybrid Li-Fi/Wi-Fi System Model.

The system's objective is to develop and sustain a network that can achieve high information throughput. Each user is equipped with an Radio Frequency (RF) antenna as well as a photodiode to ensure connectivity through Wi-Fi as well as Li-Fi. The system consists of Li-Fi , Wi-Fi bi-directional link and a central unit. The central unit monitors the whole network traffic and assigns different Li-Fi and Wi-Fi access points based on Channel State Information (CSI).

To improve the efficiency of transmission switching and signal stability, dynamic handover combined with Fuzzy Logic (FL) is also proposed. By taking advantage of FL, different connections within a fuzzy set are evaluated. Each connection is assigned a score based on their average SINR for both Li-Fi and Wi-Fi. The connection score forms the basis of evaluation. The dynamic handover mechanism is able to significantly reduce the system load as well as improve the connection stability by reducing the number of handovers.

2.4 Modulation

In general, there are three types of digital modulation technologies used to modulate digital data to light signals *(Haas et al., 2016)*.

2.4.1 Single Carrier Modulation

Single carrier modulation (SCM) uses one RF carrier carrying bits formed information. There are several forms of SCM that can be used for indoor Li-Fi communication.

Firstly, the simplest SCM to implement is On-Off Key (OOK), which is a simple form of Amplitude Shift Key (ASK). Easy to be implemented, OOK transmits data by turning on the LED representing 1 and off for 0 in high frequency, which is hard for human eyes to notice. This technique is often used in radio frequencies. When used in visible light frequencies, according to IEEE 802.15.7 (IEEE Std. 802.15.7-2011), both increasing and decreasing LED luminosity will decrease the data transmission rate.

Secondly, Pulse Position Modulation (PPM) is often used for optical fibers or infrared remote communication with little multi-path interference. It encodes M bits message into one pulse in 2M time-shift. Its transmission rate is M/T (M bits message / T second) bits per second, which is more power-efficient than OOK but less spectral-efficient. To utilise light spectrum and improve transmission performance in dim or high intensity light environment, Variable Pulse Position Modulation (VPPM) is introduced. As an optimised form of PPM, it changes the pulse width to provide a relatively fast speed in non-optimum conditions.

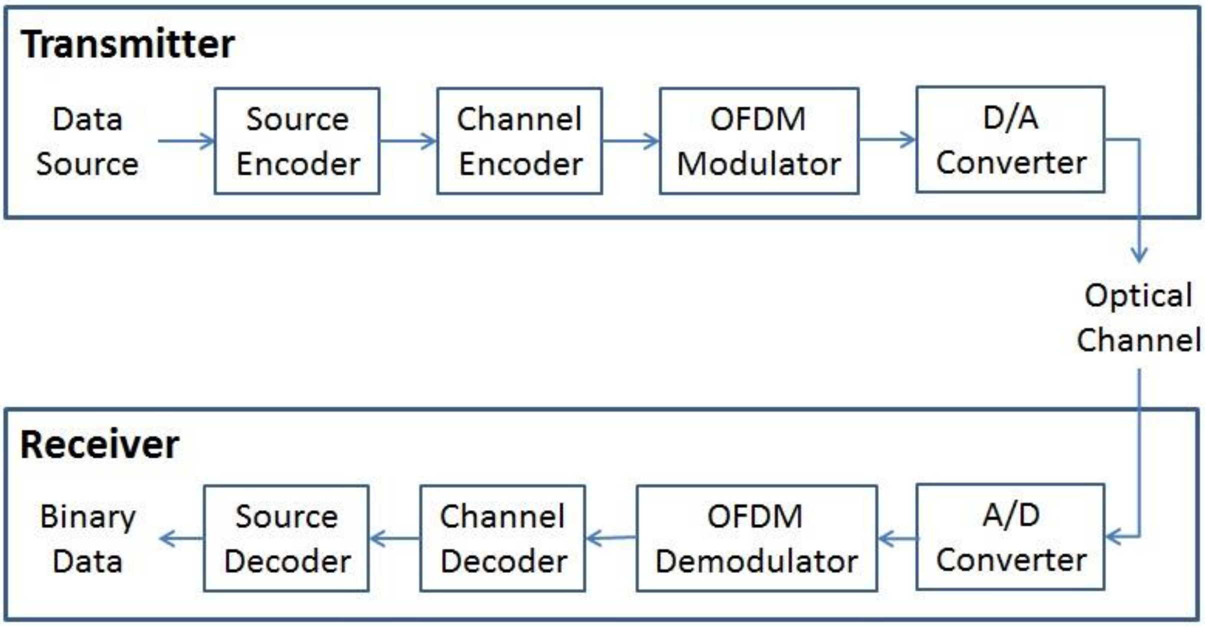
One new modulation scheme is Optical Spatial Modulation (OSM), which allows several transmitters to exist while only one transmitter is active at one time. It uses Spatial Modulation (SM) to map unique incoming data to one of the spatially separated transmitters. It is a single carrier scheme of Quadrature Amplitude modulation (QAM) which is efficient in both power and spectrum aspects for signal transmission in Li-Fi communication.

2.4.2 Multiple Carrier Modulation

Li-Fi has high transmission speed while using single carrier modulation sometimes restricts data rate. SCM can also cause many problems like non-linear signals distorted at the LED front-end and inter-symbol interference due to the frequency selectivity in dispersive optical wireless channels. To solve these problems and utilise Li-Fi high-speed transmission rate as close as possible to the Shannon limit, Multiple Carrier Modulation (MCM) is introduced.

Orthogonal Frequency-Division Multiplexing (OFDM) is one implementation of MCM used in Li-Fi transmission. It is already used in IEEE 802.11 Wi-Fi systems. In OFDM system, total bandwidth is separated into a series of orthogonal subcarriers. Parallel data streams can be transmitted concurrently through a set of subcarriers in both frequency and time aspects. This scheme can work by using the inverse Fast Fourier Transform (IFFT) at the transmitter side. The coded bipolar signal needs to be decoded by Fast Fourier Transform (FFT) at the receiver side. Some specific modifications are added to OFDM in order to suit Li-Fi communication.

OFDM can also mitigate inter-symbol interference in high transmission speed applications. Detailed transmission work-flow is shown in the graph below.



OFDM Detailed Transmission Workflow

2.4.3 Specific Modulation

Li-Fi system is special since Li-Fi transmitter is not only a simple signal transmitter but also a device for lighting. Wider bandwidth can be provided using multi colour LED as transmitters.

Colour Shift Keying (CSK) is a modulation scheme for Red-Green-Blue (RGB) LED Visual Light communication System outlined in IEEE 802.15.7. It is able to increase transmission rate and meanwhile, avoid the interference between each single colour.

2.5 Security and Reliability

Unlike coaxial fibers, the information within the optical fibre network (FTTH in Li-Fi) is transmitted in lighting series, which is hard to tap out information using the developed radio wave techniques.

2.6 Comparative Study

Here's the comparative study in technology side:

Property	Li-Fi	Wi-Fi
Spectrum	Visible Light, between Ultraviolet(UV) and Infrared Waves(IR)	Radio Wave Spectrum
Transmission Device	LED	Wi-Fi router
Speed	Up to 10Gbps; Max achieved till date is 224 Gbps	150 Mbps with WLAN-11n on average. 1-2 Gbps is achieved through WiGig/GigIR.
Bandwidth	10,000 X frequency spectrum (BW)	2.4, 4.9 and 5 GHz
Compliant Devices	IrDA, VLCC and IEEE	All IEEE 802.11 a/b/g/n/ac/ad compliant devices
Density Coverage	Works well in high density environment. Coverage is less than 10m	30 square meters

Li-Fi and Wi-Fi Comparative Study in Technology

2.7 Critical Analysis

Technology is the important part in determining whether Li-Fi is practical or not. There are many schemes of modulation. Because of Li-Fi's high transmission rate, multiple carrier modulation techniques are more suitable for it although some of them are less energy efficient than SCM. OFDM which is used widely in wireless communication is also practical for Li-Fi with specific modification. And CSK utilises the colour of LED providing high speed, no-interference modulation.

In terms of the network infrastructure, there is no mature network proposed for Li-Fi application. So we assumed FTTH as infrastructure for Li-Fi data transmission based on factors such as data transmission rate and network security.

In transmission process, electrical signal is transformed into lighting signals and vice versa. But based on the applying OFDM in VLC *(PureLiFi™, 2016)*, there are also possibilities to further improve the transmission quality and Li-Fi's compatibility with optical fibre network by skipping the process of converting light signals into electrical signals and then converting them back for visible light transmission in air. But this topic is still under discussion due to limited resources.

The high speed network connection provided by Li-Fi is introducing a new generation of network communication where large files and high quality video streams are not blocked due to bottleneck of data transmission rate.

Chapter 3. Business Analysis

3.1 Value of Li-Fi

To understand the value that Li-Fi provides, it is important to consider the possible applications of Li-Fi, including:

- Electromagnetic Interference (EMI) and electrical spark sensitive environment. For example, environments like hospitals, airplanes, explosive factories have strict rules of using electronic wave communication.

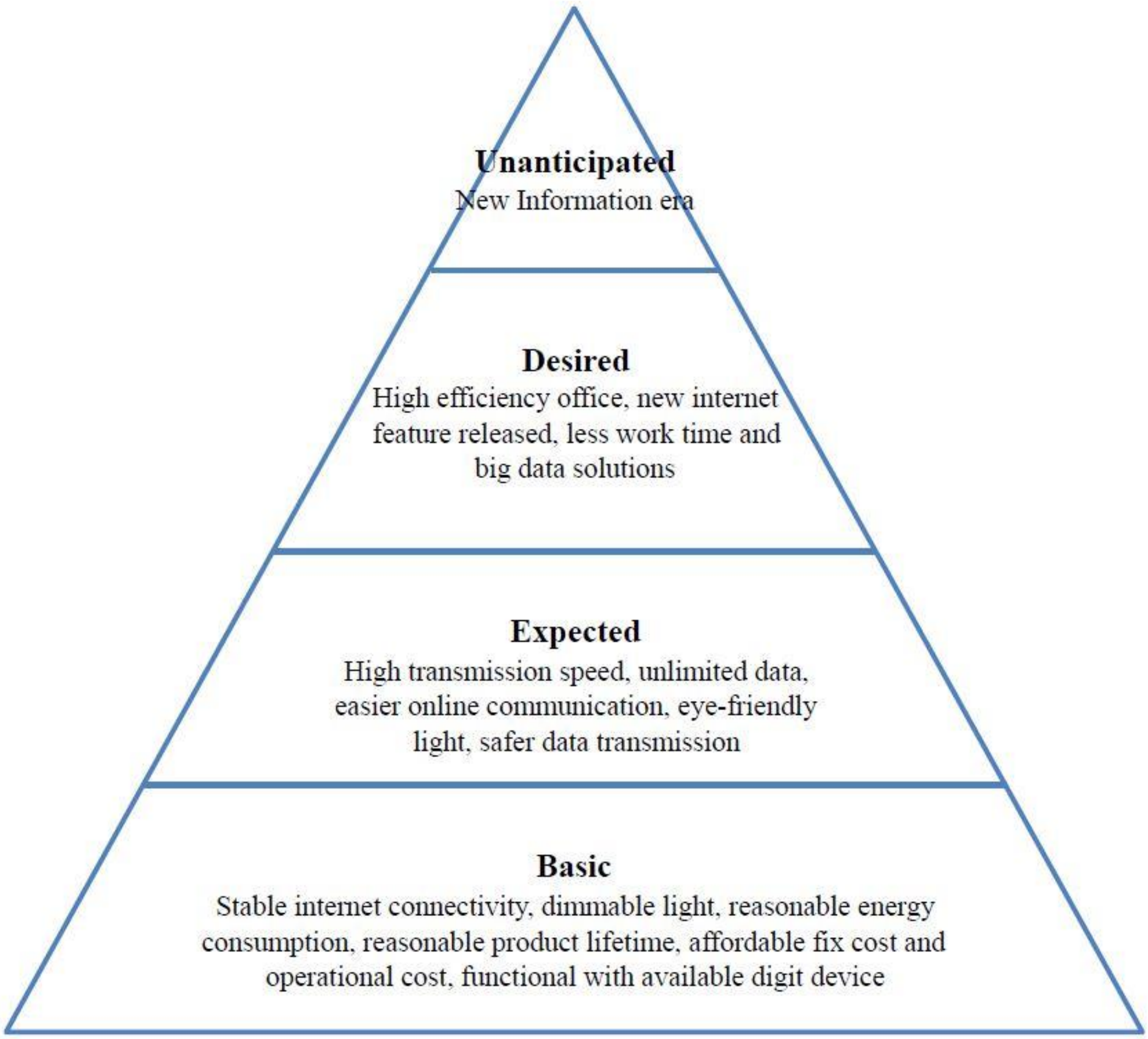
- Public areas in need of constant light. Traffic lamps, corridors, shopping malls and so on need a lighted environment constantly. Most of them provide free Internet access via Wi-Fi. Instead of having both lighting and Internet service, it can save incredible power to use Li-Fi which integrates both.

- Environments in need of extremely high transmission rate. For example, labs, R&D departments, Internet of Things (IoTs), etc.

- Environments which electronic waves are not applicable. For example, underwater environment. Electronic wave fades very quickly in water. However, light can penetrate water and suffer much smaller path loss.

3.2 Value Proposition

Together with lighting service, Li-Fi product is expected to provide a better Internet solution with smaller budget. This hierarchal model represents four layers of Li-Fi's value.



Value proposition hierarchy model

3.2.1 Basic Value

Although Li-Fi does not value itself as the substitute wireless communication technology of Wi-Fi, it has to provide data transmission service as well as, if not better, Wi-Fi does. Thus, Li-Fi has to provide stable and accessible Internet connection. To receive the data transmitted in light, customers have to possess digital devices that use particular components to receive signals. Devices with "photo detectors", the key component for Li-Fi receiver, have not yet popularised in the market. However, Apple, one of the major players in mobile phone industry, is on its way to set Li-Fi receiver in the coming new iPhones.

Li-Fi transmits data by using common LED bulbs to shed light on receivers. It has to have basic values that LED bulb has like disabled lighting, reasonable energy consumption and product lifetime. Many leading companies in lighting industry has adapted a new “pay per Lux” model .This model let users to pay for the lighting service itself instead of buying bulbs and other physical products. This has significantly cut down the fixed cost of lighting service which produces an advantage over Wi-Fi.

3.2.2 Expected Value

High transmission speed is one of the most attractive feature that Li-Fi has against Wi-Fi. Customers enjoy a very fluent and smooth internet surfing experience. Data is expected to be unlimited as a result of significant transmission speed. Unlike electronic waves, light can penetrate any physical object. Transmitting data absolutely independently within rooms or premises. This feature allows Li-Fi to experience secure online surfing, data transmitting and sharing of credential information.

Light is dimmed and fluctuated in a very high frequency which human eyes can not detect. Thus, it does no harm to human body comparing to Wi-Fi which exerts harmful influence through its electromagnetic radiation according to World Health Organisation.

Li-Fi is, with no doubt, an attractive emerging technology. Customers who pay for it are taking risks in possible deficient service, limited functions and so on. There must be an emotional and psychological reason compelling them to pay for it: to be the “cool” one among friends. So customers expect Li-Fi to be new, fancy and revolutionary.

3.2.3 Desired Value

224 gigabytes per second data transmission rate allows big data to be shared in a blink of eye which leads to higher work efficiency. Less work time is expected since less time is sacrificed in waiting for transmission to be completed. New Internet feature is expected to be released with the help of “unlimited” data transmission. For example, certain web functions are limited or disabled, because it spends most of time loading data.

3.2.4 Unanticipated Value

Unlimited data transmission will boost Big Data solutions in every industry thus value chain, value capture and business processes will experience a transforming change. Companies are not only getting ready for the Big Data era but also for IoT). This is a network of home applications, office equipments and personal devices. Users’ data can be collected and used to improve service quality, which results in a smart building, smart home and thus a smart life.

3.3 Commercialisation of Li-Fi

The success of Li-Fi commercialisation is decided by many factors: market, finance support, and substitute/competitor technologies.

3.3.1 Market Analysis

LiFi has a potential need. Applications mentioned in 3.1.1 imply Li-Fi's potential markets. It is important to know the characteristics of these markets at first when we are measuring and analysing them. Every Li-Fi spot needs to connect to a fixed network through an optical fibre link. Such connection is not available yet and the cost of rolling out an optical fibre backhaul is generally prohibitively large.

Infinite competitors and decreasing marginal revenue have forced traditional lighting industry to seek for a new way out. There are a few big names that have made efforts to transform their business models from replacement based to service-based. Capital expenditures are, to a great extent, transformed into operational expenditure. This is due to a “pay per Lux” model where customers do not pay for physical products but lighting service itself.

What service can be delivered through light is the key problem that major players face. Wireless communication technology based on lighting has proved itself as the most promising solution for hesitating incumbents. World Health Organisation, the IoT could generate $11 trillion in value globally in 2025. The number of connected devices is expected to increase to 20 percent annually over the next few years, reaching 30 billion by 2020.

Lighting value proposition has been affected by Li-Fi technology. Lighting industry has transformed its key profiting product from traditional incandescent bulbs to LED bulbs. But it is harder and harder for any lighting company to thrive or even survive as the result of massive amount of competitors and decreasing margin revenue. Therefore, a new “Service Via Lighting” business model comes to the stage.

PureLiFi, found by Harald Haas, has advantages of a variety of patents over its competitors. After securing over £14 million successfully, it paves the way for commercialising and popularising its product, Li-Fi-X, which consists of a station and an access point. It is able to achieve a transmission speed at 40 Mbps in terms of both downlink and uplink. PureLiFi also established partnership with Lucibel to provide internet via light and continue to work on technology breakthroughs.

Lucibel is a French company who values itself by innovation and design of new generation lighting products. After signing the cooperation contract with PureLiFi on 25 November 2015, it started a pilot project that marked the merge of lighting industry and Li-Fi technology.It provides various products in eluding panels, LED bulbs, lamps, ground lighting, bulkhead and etc. The products are to be installed in offices, shops, hospitals, educational institutes and industry all over the world. In

June 2015, it released a prototype that increased connectivity ability of Li-Fi by 4 times and promised Return On Investment in 6 months to 3 years.[35]

Oledcomm appears to be the biggest competitor of PureLiFi based in France, which provides museums, hospitals and smart cities with Li-Fi solutions. In particular, it is now experimentally installing Li-Fi product in local hospitals.It has two main products, namely GEOLIFE (an Indoor Positioning System that can provide a variety of Location Based Services) and LIFENET.

3.3.2 Comparative Study

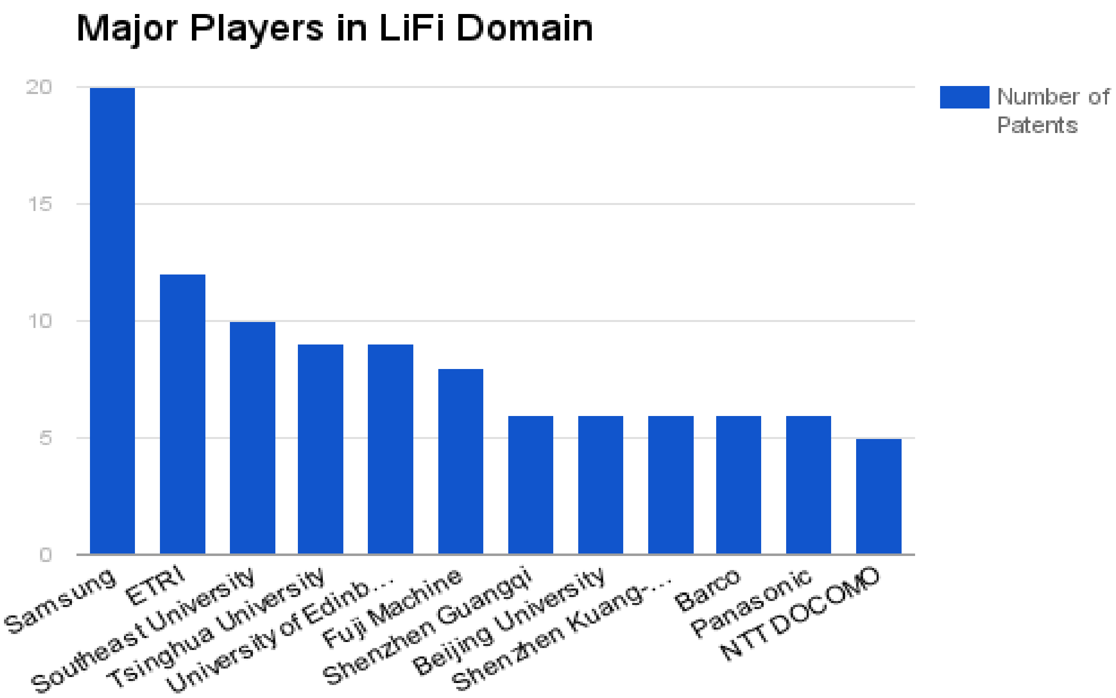
Despite a nascent concept, Li-Fi is developed not only in technology, but also in business world, growing in the range of companies. There are increasingly more companies in the field of VLC attracting ventures and gaining investment by the year of 2016.

Company Name	Total Funding	Investors	Location
PureLiFi	$14.6+ Million	ITI scotland; Old College Capital; London Scottish; Investment partners	Edinburgh, City of Edinburgh, the UK
Enlighted	$55.64+ Million	Rockport Capital Partners; Kleiner Perkins Caufield & Byers; Intel Capital; Draper Nexus Ventures; Draper Fisher Jurvetson	Dublin, Ireland
Electric Imp	$23 Million	rampart capital LLC, PTI Ventures; Rampart Capital Corp; Foxconn Technology Group	Cambridge, Cambridgeshire, the UK

Company Name	Total Funding	Investors	Location
Everything	$7 Million	BHLP; Dawn Capital; Cisco; Atomico London, the UK;	Ontario, Canada
SmartThings	$15.5 Million	Slow Ventures; A-grade Investments; Start Fund; CrunchFund; SV Angel	Washington, DC, USA
Revolv	$ 7.32 Million	SK Ventures; Liberty Global Ventures; Foundry Group; American Family Insurance	Boulder, CO, USA
ByteLight	$4.25 Million	The eCoast Angel Network; Motorola Solutions Venture Capital; Sand Hill Angels; Flywheel Ventures	Boston, MA, USA
LIFX	$13.32 Million	Sequoia Capital	San Francisco, CA, USA

Comparison of Li-Fi Companies

Enterprises and organisations compete not only in gaining capitals and financial investments, but also in acquiring patents to take the initiative and stand out.



Top 12 Entities Researching in Li-Fi Domain And Filing Patents

Samsung ranks at the first place with 26 patents followed by the University of Edinburgh that owns 6 patents. ETRI is at the third spot because of its development of LubiNet, which is able to deliver digital data using LED lights. Next, there are two positions taken by universities. It should be noted that as the father of Li-Fi, Professor Harald Haas is the inventor of many patents filed by the University of Edinburgh. Moreover, he has also filed several patents with Jacobs University Bremen and NTT DOCOMO. Apart from tech Goliath – Samsung, NTT Docomo, Panasonic – Koriist, SamsaraHQ and other ingenious startups are also making an effort to shine.

Capitalisation of the overall industry of Li-Fi is increasing without doubt, however, it is not a positive trend to invest currently. The real-world market and applications of Li-Fi products are still limited with more and more players showing up. Appropriate competition would be a motivation of developing the technology and relative products. However, with limited market size and customer base, it leads to destruction of investment since Venture Capitals and investors have their different perspectives and predictions on which is the most potential company in this field. As a consequence, it may slow down the speed of successful commercialisation of an enterprise in the real world to some degree.

If the trend of increasing Li-FI investment continues, it will certainly help speed up the roll out and popularisation of Li-Fi technology, whose growth in capitalisation will in return trigger more startups or companies in Li-Fi. One the one hand, it can add to the motivation and variety of the field of VLC. On the other hand, however, it will raise the level and intensity of competition in commercialising, which maybe harmful for these technological startups in collecting funds and investments with the limited resources in the whole market.

3.4 SWOT Analysis

Below is the SWOT analysis of Li-Fi products:

	Helpful	**Harmful**
Internal	**Strength** • High transmission rates. The use of LED's and operating in the visible light spectrum makes the data transmission faster when compared to Radio waves. • Solves the radio frequency spectrum crisis. • Useful where RF cannot be used. In hospitals and industries where RF can be harmful, Li-Fi could make a suitable replacement to Wi-Fi. • Low power consumption because of the use of LED lights. • Security, confined to a room. Since, Li-Fi is short ranged, the chance of eavesdropping is less. • Ubiquitous availability. Since, it operated under the Visible light spectrum it is easily available	**Weakness** • Short Coverage. The range of Li-Fi is limited to the source of light. Being short distant can be a weakness as the cost for investing in LED's to increase the network coverage increases. • Not widely used. There are very few applications or companies that use Li-Fi. This is a weakness for Li-Fi to establish as a brand and overcome the market barriers.

	Helpful	**Harmful**
External	**Opportunity** • Expand / Replace Wi-Fi Technology. Li-Fi has the potential to replace or complement the Wi-Fi technology. • Multi-transmissions using Multi-LEDs. Li-Fi has the capacity to maximize the throughput by using multiple LED’s	**Threats** • Currently fewer applications. There are very few applications currently that need such high data transmissions. • Light pollution. The use of LED’s for continuous data transmissions can lead to light pollution.

SWOT Analysis of Li-Fi Products

Chapter 4. Policy Analysis

4.1 Standardisation

The need for a standard for VLC was first proposed by Professor Nakagawa's working group at the Nakagawa Laboratory, Keio University, Japan. They foresaw the widespread use of LEDs and realised the problems of inter-product interference and interoperability. Hence, Professor Nakagawa established the Visible Light Communications Consortium (VLCC) in 2003. With major firms like Fuji, NEC Lighting, Sony Corporation and Toshiba Corporation as members, the objective was to standardise VLC.

They proposed two standards CP-1221 (visible light communication standard) and CP-1222(visible light ID system standard) at JEITA in 2007 standard for visible light communication *(Haruyama, S.V. and Chairman, 2008)*.

In 2009, IEEE's task group on VLC met for the first time. At the meeting a decision was made to develop standards for VLC (IEEE, 2003). They developed the IEEE 802.15.7 standard for VLC at the MAC and PHY layers.

The modulation techniques supported by IEEE 802.15.7 include on-off keying (OOK), Variable pulse position modulation (VPPM) and Colour shift keying (CSK) *(gordonpovey, 2012)*. With the advent of Li-Fi which propagates multi-user bidirectional communication as opposed to a point-to-point VLC system, the existing standards need to be revised *(Haas et al., 2016)*.

The modulation techniques currently supported by IEEE 802.15.7 prove to be spectrally inefficient at higher modulation speeds due to the effects of inter-symbol interference *(Tsonev, Videv and Haas, 2013)*. Hence orthogonal frequency multiple division multiplexing OFDM was proposed as a multi carrier modulation technique for Li-Fi. The effectiveness of IEEE 802.15.7 is now being reconsidered, given the compatibility of OFDM with widely used standards such as IEEE 802.11 and LTE.

4.2 Security

Li-Fi is inherently secure by virtue of the medium characteristics. Visible light cannot penetrate through walls and is confined to a closed environment. Security is managed by the Application and Presentation layers of the protocol stack. Given that Li-Fi standards are at the MAC and PHY layers, security is not a primary concern.

4.3 Role of Governments

Governments serve as an important policy instrument in the commercialisation of a new and disruptive technology.

In the case of Li-Fi, governments may have to intervene since Li-Fi enabled LEDs would require to be in the "always on" state. An analysis and forecasting of the possible increase in power consumption would have to be undertaken. Based on the analysis, a roll out policy would have to be drafted for Li-Fi.

The governments would be required to draft and implement policies to initiate the shift from RF to VLC in order to mitigate the impending "RF Spectrum Crisis".

Chapter 5. Li-Fi's Applications

5.1 Applications

1) Data Center Migrations

Many companies go through the problem of slow data transition usually when they are migrating their data centre from one location to another. The Li-Fi technology enables quick transmission of data and hence increasing the productivity.

Most Fortune 500 companies invest time and money in data centre migrations chasing for improvement in security and performance *(ServerCentral. 2016)*. Typically, it would take approximately 17 minutes to transfer 1 Tb data with all the infrastructure in place, under the assumption that transfer speed is 1 Gbps. At the speed of 23 Gbps, it would take much less time. Therefore, Li-Fi would be the perfect fit for data centre migrations in order to save both money and man hours.

2) Solution to the Potential Radio Frequency Spectrum Crisis

An important application of Li-Fi to solve the Radio Frequency spectrum crisis caused by wireless networks. With the increasing demand of wireless networks, Li-Fi can help in reducing the load where available. Using Li-Fi can help specifically in cases where there is a bottleneck for downlink.

3) Smart Lighting

Li-Fi technology can play a major role in establishing any private or public hotspots just by the street lamps. Similarly, this technology can be used for sensor communications infrastructure to monitor and control lighting and data. So far smart lighting has been proposed with the idea of optimising energy consumption from lights and saving energy wherever possible. It involves using sensors in order to detect when light can be saved, ie by automatically dimming light. Saving energy would not only mean being environment friendly but also greatly reduce the costs spent on energy.

Hence by using a technology such as Li-Fi or smart lighting, a light bulb is not only able to detect automatically when to save power but also to connect to the Internet at high data transmission rates. It is truly “smart” because of capabilities like transmission of multimedia content and GPS support. Therefore, it is especially useful in areas where radio waves are not traditionally available.

4) Mobile Connectivity

Mobile devices with Li-Fi have an enormous potential market. Current technology cannot fully utilise the phone’s capacity: Bluetooth is slow, unstable and hard to manage while Wi-Fi is unstable and limited in terms of speed. In contrast, Li-Fi is stable and fast, providing security with short range links. Laptops, smart phones, tablets and other mobile devices can interconnect directly using Li-Fi, making it perfectly fit mobile telecommunications and is well suitable for mobile connectivity.

5) Mining and Petrochemical Industries

Mining and petrochemical industries are important but dangerous. In many dangerous situation, like containing amount of metal, full of explosive gas or extremely dry, using electromagnetic for communication is of high risk producing spark causing explosion. Li-Fi is a safe alternative which can be used in such hazardous environments. Using visual light as transmission medium, Li-Fi avoids spark during the process of transmission. It is a potentially a safe alternative for using of data communications in the mining and petrochemical industries. Since, the risk of electromagnetic interference due to radio waves can be avoided.

6) Hospital & Healthcare

Radio frequency spectrum introduced by wireless communication system such as Wi-Fi will probably inference with the medical equipments *(Berger and Gibson, 2013)* resulting in malformed monitoring results. Thus Li-Fi can be a great means of communication.

In addition, patients in hospitals will be more sensitive to influence introduced by the radio frequency spectrum in that excessively exposure under radio polluted will increase the change that people have cancer by causing cells carcinogenesis. *(Berger and Gibson, 2013)*. And thanks to Light Fidelity communication, Li-Fi, which is operating in visual light spectrum, will bring no radio frequency spectrum to the environment.

What’s more, researchers in North Korea also demonstrated that Li-Fi can also apply for ElectroEncephaloGraph (EEG) readings *(Motherboard, 2016)*, through which light signals are magnified and distorted in different colours.

7) Aviation Industry

Li-Fi is a boon in the aviation industry as using Li-Fi will help in reducing the weight if a freight and the LED lights can help the aviation industry to improve their In-flight entertainment experience and can also be fused with the passengers’ smart phones.

Traditionally, there is no Internet connectivity inside flights due to the possible interference of the RF signals with the cockpit communications system. Although nowadays the aircrafts are well shielded from any interference, but the aviation industry is still reluctant to allow for RF signals to be used while in flight.

Li-Fi could be used to provide Internet within flights, without causing any interference with the communication system. The overhead reading lights could be well harnessed as Li-Fi transceivers.

8) Submarine Communications

Radio frequency is not susceptible to water. Current underwater Remotely Operated underwater Vehicles(ROVs) work generally in good condition, however, their exploratory ranges are limited by the length and freedom of tethers. Replacing these inconvenient wires with a submerged, high-powered lamp, these devices are not only able to explore more deepwater region, but to guarantee submariners' communication via headlamps as well, processing data autonomously and send what they found up to the surface. *(IJAER, international journal of applied engineering research, engineering journals, engineering research journal publisher in India, mechanical journals in India, science journal publishers in India, no date)*

It provides a more stable and vital communication where shipwreck or other catastrophes take place. People eager to establish a link of communication no longer are trapped with the crowded traditional channels. Li-Fi can be further implemented in the underwater oil rigs detection and communication industry where radio signals are dangerous *(Thawali and Vishvajeet, 2016)*.

9) Vehicles & Transportation

The use of LED headlights and tail-lights is another application of Li-Fi in the transportation industry. With the application of Li-Fi in street lamps, traffic signals, this technology can be used for vehicle-to-vehicle and vehicle-to-roadside communications. This can also be applied for road safety and traffic management.

In traffic signals, Li-Fi guarantees the car-to-car communication with LED which reduces the accident rates and helps in traffic management. The prototype with an optical filtering is to be enhanced, improving the signal to noise ratio as a result of filtering the useful light to around 10-6 BER in a distance over 50 meters *(Cailean, 2016).*

10) Location Based Services

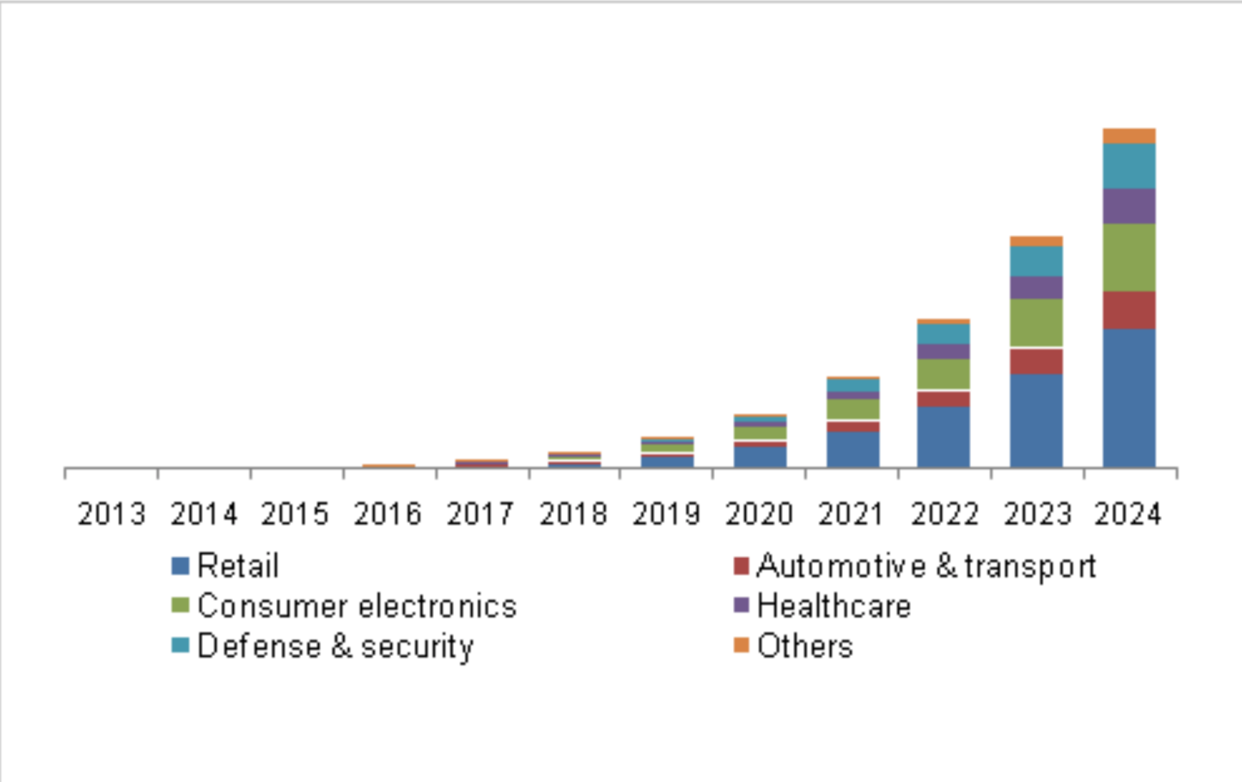
The Li-Fi technology can be used for location based services. One of the examples is location based advertisements. The idea is to advertise based on the user's location. High accuracy location-specific information services such as advertising and navigation that enables the recipient to receive appropriate, pertinent information in a timely manner and location.

11) Peeking Into the Future

The Li-Fi though not extensively used can be used for the applications developed in the future which demand for high transmission rates. Currently, applications like Youtube, Netflix, need good data speed to stream good quality video. With the advancement in technology, there will probably be need of high data transmissions. In such cases, Wi-Fi could be very useful. The applications using Machine Learning and Artificial Intelligence technologies would also rely on Li-Fi.

5.2 Critical Analysis

To have this technology commercialised, exploring and developing realistic development is vital.. All of the above mentioned applications are absolutely necessary. These are the applications that Li-Fi needs commercialisation in the market.



VLC Market Share by Application in the United States, 2013 - 2024

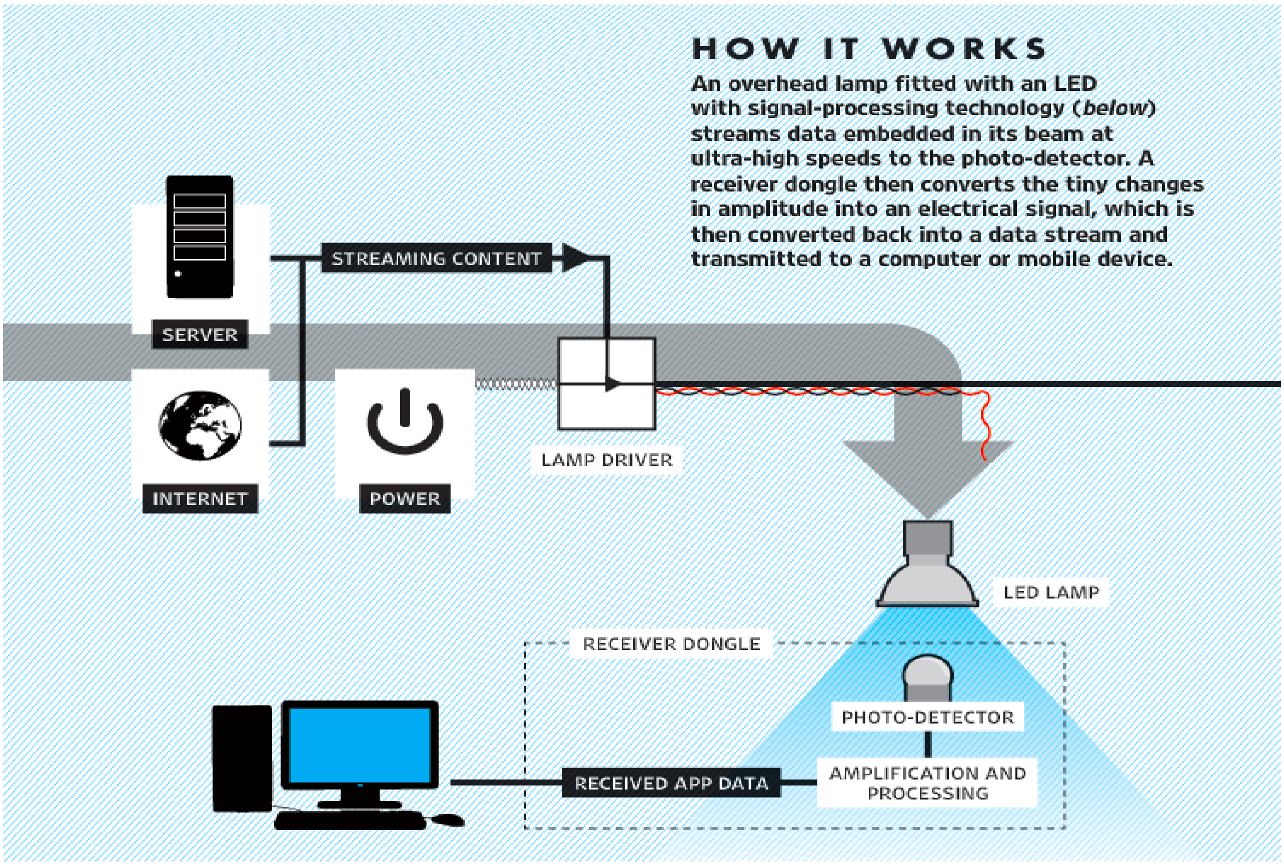
Chapter 6. Case Study - PureLiFi

6.1 Introduction to PureLiFi

Founded by Professor Harald Haas, PureLiFi has made a long way from a startup to the leader force in Li-Fi industry within eight years. It was initially spin-out from University of Edinburgh. The famous TED talk in 2011 marked that PureLiFi's achievement in naturalising product in the first phase. The first generation of PureLiFi was released in January 2014 which has been replaced by Li-Flame in late 2014 and Li-Fi in early 2016. Instead of holding exclusive technology of Li-Fi, PureLiFi works with many technology partners, solution providers, and hardware manufacturers.

6.2 Technology Analysis

The main product of PureLiFi is Li-Fi-X. It's a light bulb that emits a stream of photons, which is observed as a visible light. The LED bulbs are semiconductor devices. When there is a current emitting to the light bulb, the signal can be modulated at extremely high speeds, and this modulation is imperceptible to the human eyes. By using this technique, high speed information can be transmitted from a LED light bulb. This device massively reduced the receiver's footprint and improved speeds to 40 mbps downlink and uplink.



How does LiFi work? Available at PureLiFi's Website

6.3 Financial Analysis

PureLiFi is a private limited with share capital. It was founded in February 22, 2011. Based on PureLiFi's information on Crunchbase, pure Li-Fi mainly has 5 rounds of funding with four major investors: London & Scottish Investment Partners, Old College Capital, Scottish Investment Bank, and Temasek Holdings. Most recently, they raised $7 million Series B funding in July 15, 2016. The total amount of fundings is of PureLiFi is $25.89 million.

PureLiFi's financials Overview is shown in the following chart:

	Amount	Comparing to Previous Year
Cash in Bank	510.8k	21.44% increase
Net Worth	162.65k	78.95% decrease
Current Liabilities	606.53k	154.79% increase
Total Assets	769.18k	58.24% increase

Financial Overview of PureLiFi

6.4 Summary

Although PureLiFi has released for three years and had many upgrades, it is still unknown to most outside the industry. PureLiFi doesn't sell any of its devices on its website or Amazon. There is little information about PureLiFi on the internet compared with most Wi-Fi products.

Chapter 7. Conclusion

7.1 Proposal

Our suggestion is to wait and watch how the current investment in Li-Fi pays off. While waiting, we should monitor the development of technologies that have a strong potential to get commercialised in the future. Such technologies could give rise to applications that require high transmission speeds, that Li-Fi promises.

In terms of technology, Li-Fi is worth investing. For instance, Hybrid Li-Fi/Wi-Fi model, which combines Li-Fi and Wi-Fi within the same network, is an ideal reason for investing into Li-Fi. Such a network will have better capability of multi-user access as well as a higher total network throughput. It would be late to invest if Li-Fi is totally mature.

However, it is not all about technology. Technology has to be complemented by business, just like Li-Fi has to be complemented by Wi-Fi. The research in Li-Fi has focused around data transmission rates and modulation techniques. A shift is required to explore the possible applications of Li-Fi. With the advent of IoT, application of Li-Fi seems imminent. But further research is required to explore the nuances of each such domain of application.

The Li-Fi market still seems not competitive enough. First, the current products including Li-Fi-X, GEOLIFE and LIFENET are not mature. And second, the limited market size makes it difficult to enter the industry and take a market share.

Li-Fi firms are also lacking customers. Although Li-Fi has been in the market for a very long time, there are very few products for sale in the open market. On Amazon.com, there are only two or three Li-Fi products, and all of them do not have much sales. It would be hard to commercialise the products, if the user base is limited.

It also costs too much to construct the required infrastructure, including more optical fibers, special LED bulbs and detectors in personal digital devices. These capital costs are not compensated by the projected benefits, and hence result in a low ROI. Although Li-Fi has the capability of 224 Gbps in labs, it seems that at current stage, we do not really need that high transmission rate.

PureLiFi just got a 14 million $ funds in July 2016. It is wise to wait and see how they will use this fund and what they can achieve then to invest. Li-Fi should prove over a period whether it is worth investing.

7.2 Recommendation

Li-Fi’s high transmission rate is redundant for household usage. The cost of optical fibers is lesser than the cost of building a new infrastructure for Li-Fi. However, Li-Fi is suitable in situations that involve huge amount of data transmission like data center migration or robot manipulation. Therefore, Li-Fi companies should pay more attention to specific business areas where Li-Fi’s high transmission capability can be fully utilized.

Li-Fi may become more feasible with the advent of IoT. A comprehensive network of sensors would need to be connected using multiple access and supporting a high transmission rate. Companies can research on how to utilize existing LEDs to make our homes into a smart home.

In summary, Li-Fi firms need to focus their effort into the exploration of domains where Li-Fi could prove to be the most optimized solution. If Li-Fi firms want to make profits, they need to emphasize on the business and marketing strategy , instead of solely being driven by the technological advancements like high transmission speeds. They should find a specific target market and focus on disrupting it by harnessing the value proposition of Li-Fi.

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