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Li-Fi Technology: Data Transmission through Visible Light

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***Abstract:** Li-Fi stands for Light-Fidelity. The technology is very new and was proposed by the German physicist Harald Haas in 2011. Li-Fi provides transmission of data through illumination by sending data through an LED light bulb that varies in intensity faster than human eye can follow. In this paper, the authors will discuss the technology in detail and also how Wi-Fi can be replaced by Li-Fi. Wi-Fi is useful for general wireless coverage within buildings while Li-Fi is ideal for high density wireless data coverage in confined areas where there are no obstacles. Li-Fi is a wireless optical networking technology that uses light emitting diodes (LEDs) for transmission of data. The term Li-Fi refers to visible light communication (VLC) technology that uses as medium to deliver high-speed communication in a manner similar to Wi-Fi. Li-Fi provides better bandwidth, efficiency, availability and security than Wi-Fi and has already achieved high speeds in the lab. In the present paper the authors will give a detailed study on Li-Fi technology, its advantages and its future scope.*

***Keywords:** Light Fidelity; LED; VLC; Wi-Fi; Bandwidth.*

I. Introduction

Professor Harald Haas, the Chair of Mobile Communications at the University of Edinburgh, is recognized as the founder of Li-Fi. He coined the term Li-Fi and is the co-founder of pureLiFi. He gave a demonstration of a Li-Fi prototype at the TED Global conference in Edinburgh on 12th July 2011. He used a table lamp with an LED bulb to transmit a video of a blooming flower that was then projected onto a screen. During the talk, he periodically blocked the light from the lamp with his hand to show that the lamp was indeed the source of the video data. Li-Fi can be regarded as light-based Wi-Fi, i.e. instead of radio waves it uses light to transmit data. In place of Wi-Fi modems, Li-Fi would use transceivers fitted with LED lamps that could light a room as well as transmit and receive information. It makes use of the visible portion of the electromagnetic spectrum which is underutilized. Li-Fi can be considered better than Wi-Fi because there are some limitations in Wi-Fi. Wi-Fi uses 2.4 – 5 GHz radio frequencies to deliver wireless internet access and its bandwidth is limited to 50-100 Mbps. With the increase in the number of Wi-Fi hotspots and volume of Wi-Fi traffic, the reliability of signals is bound to suffer. Security and speed are also important concerns. Wi-Fi communication is vulnerable to hackers as it penetrates easily through walls. In his TED talk, Professor Haas highlighted the following key problems of Wi-Fi that need to be overcome in the near future:

a) Capacity: The radio waves used by Wi-Fi to transmit data are limited as well as expensive. With the development of 3G and 4G technologies, the amount of available spectrum is running out.

b) Efficiency: There are 1.4 million cellular radio masts worldwide. These masts consume massive amounts of energy, most of which is used for cooling the station rather than transmission of radio waves. In fact, the efficiency of such stations is only 5%.

c) Availability: Radio waves cannot be used in all environments, particularly in airplanes, chemical and power plants and in hospitals.

d) Security: Radio waves can penetrate through walls. This leads to many security concerns as they can be easily intercepted.

Li-Fi addresses the aforementioned issues with Wi-Fi as follows:

a) Capacity: The visible light spectrum is 10,000 times wider than the spectrum of radio waves. Additionally, the light sources are already installed. Hence Li-Fi has greater bandwidth and equipment which is already available.

b) Efficiency: LED lights consume less energy and are highly efficient.

c) Availability: Light sources are present in all corners of the world. Hence, availability is not an issue. The billions of light bulbs worldwide need only be replaced by LEDs.

d) Security: Light of course does not penetrate through walls and thus data transmission using light waves is more secure.

Table-1: Advantages of Li-Fi

Light	LEDs produce more light per watt than do incandescent bulbs
ON-OFF Time	LEDs can light up very quickly
Toxicity	Unlike fluorescent lamps, LEDs do not contain mercury
Free Band	Li-Fi makes use of a free band that does not need any licensing
High Speeds	It offers theoretical speeds in the order of Gigabits per second
Airlines	Li-Fi can be used safely in aircrafts without affecting airline signals unlike Wi-Fi
Healthcare	It can be integrated into medical devices and in hospitals as no radio waves are involved
Underwater	Wi-Fi does not work underwater but Li-Fi does and hence can be used for undersea explorations
Traffic Control	Li-Fi can be used on highways for traffic control applications. Cars can have LED based headlights and LED based backlights that can communicate with those of other cars and prevent traffic accidents
Street Lamps	Every street lamp can be converted into a free data access point
Spectrum Relief	The issues of the shortage of radio frequency bandwidth can be sorted out by Li-Fi

The applications of Li-Fi are derived from many of these benefits and will be studied in detail in later sections.

Frank Deicke, who leads Li-Fi development at Fraunhofer Institute for Photonic Microsystems in Dresden, Germany, has said that Li-Fi can achieve the same data rates as USB cables which is challenging for wireless technologies such as Bluetooth and Wi-Fi. He also cites another advantage of Li-Fi being that the latency of Li-Fi is in the order of microseconds where as that of Wi-Fi is in the order of milliseconds.

With the above benefits encouraging us to adopt this new technology, the actual need for Li-Fi can be confirmed from Cisco's Visual Network Index which suggests that user demand is increasing faster than gains in spectral efficiency. By 2015, traffic from wireless devices is expected to exceed that from wired devices. Such increases in network traffic require significant changes in how we think of wireless communication and Li-Fi may be the change that we need.

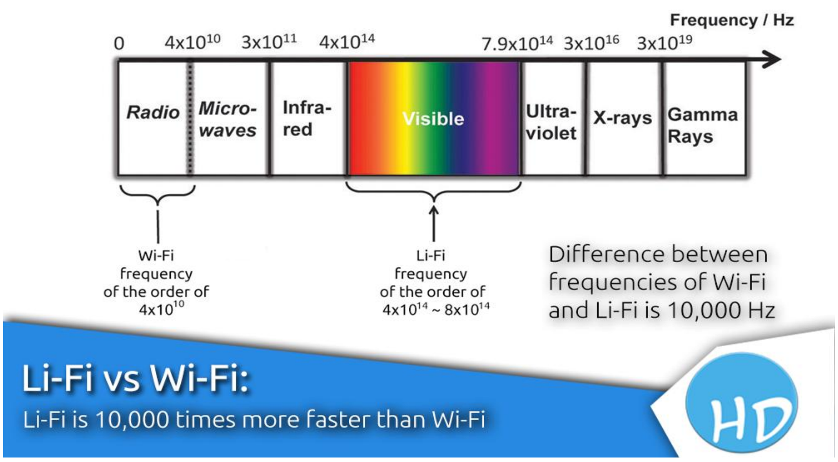

Fig-1: Li-Fi and Wi-Fi Spectrum Usage

Table-2: Comparison between Li-Fi and Wi-Fi

Parameter	**LI-FI**	**WI-FI**
Speed	High	High
Spectrum	10,000 times broader than that of Wi-Fi	Narrow spectrum
Data density	High	Low
Security	High security due to non-penetration of light through walls	Less secure due to transparency
Reliability	Medium	Medium
Bandwidth	High due to broad spectrum	Low
Transmit/receive power	High	Medium
Ecological Impact	Low	Medium
Device-to-device connectivity	High	High
Obstacle interference	High	Low
Bill of materials	High	Medium
Market maturity	Low	High
Latency	In the order of microseconds	In the order of milliseconds

II. WORKING OF LI-FI

General Working Principle

Light emitting diodes (LEDs) can be switched on and off faster than the human eye can detect since the operating speed of LEDs is less than 1 μs, thereby causing the light source to appear to be continuously on. This invisible on-off activity enables data transmission using binary codes. Switching on an LED is binary '1', switching it off is binary '0'. It is possible to encode data in light by varying the rate at which LEDs flicker on and off to give different strings of 1s and 0s. Modulation is so rapid that humans cannot notice it. A light sensitive device (photo detector) then receives the signal and converts it back into original data.

This method of using rapid pulses of light to transmit information wirelessly is technically referred to as Visible Light Communication (VLC).The term Li-Fi has been inspired due to its potential to compete with conventional Wi-Fi. The VLC uses visible light between 400 THz (780 nm) and 800 THz (375 nm) as the optical carrier for data transmission and for illumination.

Data rates of greater than 100 Mbps can be achieved by using high speed LEDs with adequate multiplexing. Parallel data transmission using arrays of LEDs where each LED transmits a separate stream of data can be used to increase the VLC data rate. Though the lights have to be kept on in order to transmit data, they can be dimmed to the point that they are not visible to humans but still be capable of transmitting data.

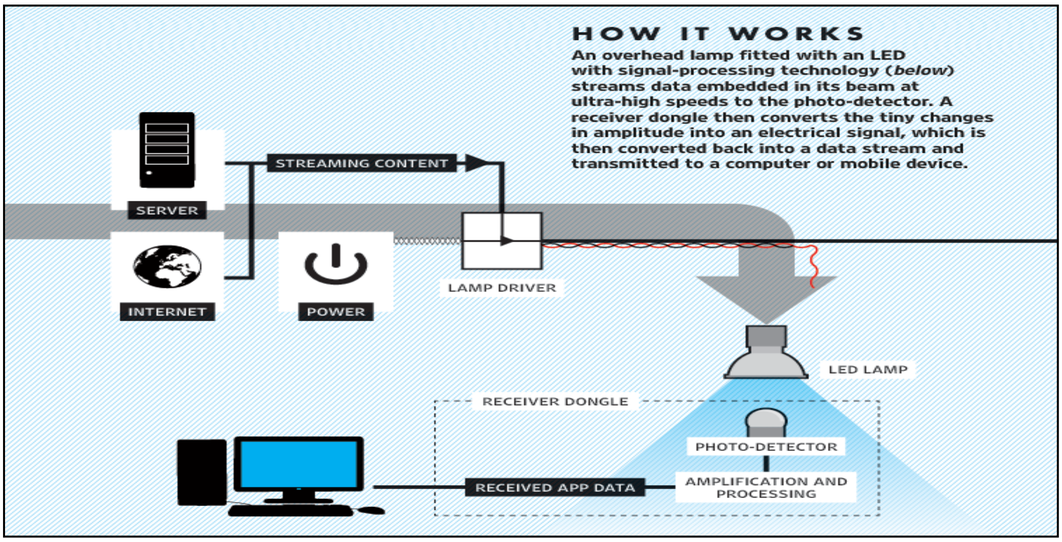

Fig-2: Working of Li-Fi

2.1 Technical Aspects and Modulation

VLC refers to any use of the visible light portion of the electromagnetic spectrum to transmit information. A VLC interest group is certified by the IEEE 802.15 with the final standard being approved in 2011. The standard of VLC specifies VLC consisting of mobile-to-mobile (M2M), fixed-to-mobile (F2M) and infrastructure-to-mobile (I2M) communications. The main purpose of VLC is to focus on medium-range communications for intelligent traffic systems at low-speed and on short-range mobile to mobile and fixed to mobile communications at high speeds to exchange data. Data rates are supported from some 100 kbps up to 100 Mbps using various modulation schemes.

Li-Fi communication is modelled after protocols established by the IEEE 802 workgroup. It defines physical layer (PHY) & media access control (MAC) layer for VLC/Li-Fi.

The MAC layer supports 3 multi-access technologies: peer-to-peer, star configuration and broadcast mode. It also handles physical layer management issues such as addressing, collision avoidance and data acknowledgement protocols. The physical layer is divided into 3 types: PHY I, II, III and employ a combination of different modulation schemes.

In order to actually send out data by means of LEDs, it is required to modulate these into a carrier signal. The carrier signal consists of light pulses sent out at short intervals. The manner in which this is done depends on the modulation scheme employed.

Li-Fi systems use the following different modulation schemes:

1. On-Off Keying (OOK): The 802.15.7 standard uses Manchester coding so that the period of positive pulses is same as the period of negative ones, however this doubles the bandwidth required for transmission. For higher bit rates, run length limited (RLL) coding is used which is spectrally more efficient. Dimming is supported by adding an OOK extension which adjusts the aggregate output to the correct level.
2. Variable Pulse Position Modulation (VPPM): PPM encodes the data using the position of the pulse within a set time period. The duration of the period containing the pulse must be long enough to allow different positions to be identified. VPPM is similar to PPM but it allows the pulse width to be controlled to support light dimming.
3. Colour Shift Keying (CSK): This is used if the illumination system uses RGB-type LEDs. By combining different colours of light, the output data can be carried by the colour itself and hence the intensity of the output can be near constant. Mixing of RGB primary sources produces different colours which are coded as information bits. The disadvantage is that it increases the complexity of the transceivers.
4. Sub-Carrier Inverse PPM (SCIPPM): This method is divided into two parts (1) sub-carrier part and (2) DC part. The DC part is used only for lighting or indicating. When there is no requirement for lighting or indicating, SCPPM (Sub-Carrier PPM) is used in order to save energy.
5. Frequency Shift Keying (FSK): In this method, data is represented by varying the frequencies of the carrier signal. Before transmitting two distinct values (0 and 1), there needs to be two distinct frequencies.
6. SIM-OFDM (Sub-Carrier Index Modulation OFDM): This is a new approach to transmission in which an additional dimension is added to conventional 2D amplitude/phase modulation (APM) techniques such as quadrature amplitude modulation (QAM) and amplitude shift keying (ASK). The key idea is to use the sub-carrier index to convey information to the receiver.

2.2 LED as Light Source

The most important requirement for a light source in order to serve communication purposes is the ability to be switched on and off repeatedly in very short intervals of time. Due to their ability to be switched on and off rapidly, LEDs are suitable light sources for Li-Fi. LEDs offer many benefits over fluorescent lamps and incandescent lamps such as higher efficiency, environment-friendly manufacturing, flexibility of design, longer useful lifetimes and improved spectrum performance.

LEDs emit light when the energy levels change in the semiconductor diode. This change in energy generates photons, some of which are emitted as light. The wavelength of emitted light depends upon the difference in energy levels and the type of semiconductor material used to form the LED chip. Solid-state design allows LEDs to withstand vibration, shocks, frequent switching and extremes of environment without compromising their long useful lives of typically more than 100,000 hours.

The basic LED consists of a semiconductor diode chip mounted in the reflector cup of a lead frame that is connected to electrical (wire bond) wires, and then encased in a solid epoxy lens. The variations in data rate with the size of LEDs are very important in Li-Fi technology. Different data rates can be achieved with different sized LEDs. Normal sized LED bulbs can be reduced to micro-LEDs which handle millions of variations in light intensity. A micro-LED light bulb can transmit 3.5 Gbps and data rates of more than 10 Gbps are possible. The micro LED bulbs allow the light stream to be beamed in parallel thereby transmitting huge amounts of data in terms of Gbps.

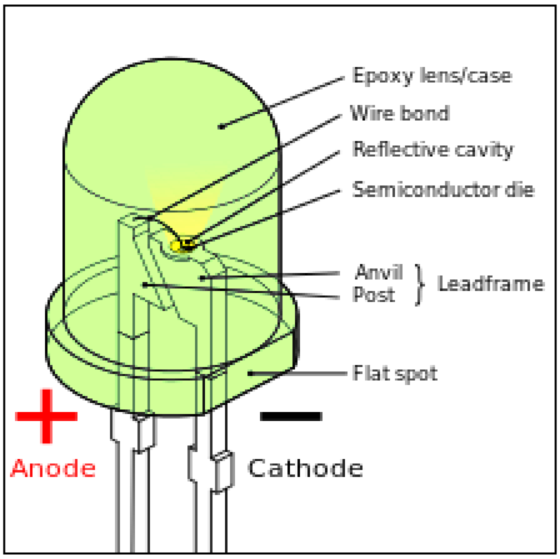

Fig-3: LED

2.3 Usage Models

Within a local Li-Fi cloud, several data based services are supported through a heterogeneous communication system. Initially, the Li-Fi Consortium defined different types of technologies to offer secure, reliable and ultra-high-speed wireless communication interfaces. These included giga-speed technologies, optical mobility technologies and navigation, precision location and gesture recognition technologies. For giga-speed technologies, the Li-Fi Consortium defined Giga Dock, Giga Beam, Giga Shower, Giga Spot and Giga MIMO models to tackle different user scenarios for wireless indoor and indoor-like transfers of data. Giga Dock is a wireless docking solution that includes wireless charging for smart phones tablets or notebooks, with speeds up to 10 Gbps. Meanwhile, the Giga Beam model is a point-to-point data link for kiosk applications or portable-to-portable data exchanges. Thus a two-hour full HDTV movie (5 GB) can be transferred from one device to another within four seconds.

Giga Shower, Giga Spot and Giga-MIMO are the other in-house communication models. On one side, a transmitter or receiver is mounted into the ceiling connected to, say, a media server. On the other side are portable or fixed devices on a desk in an office, in an operating room, in a production hall or at an airport. Giga Shower provides unidirectional data services via many channels to multiple users with gigabit-class communication speed over several meters. This is like watching TV channels or listening to different radio stations where no uplink channel is needed. In case Giga Shower is used to sell books, music or movies, the connected media server can be accessed via Wi-Fi to process payment via a mobile device. Giga Spot and Giga

MIMO are optical wireless single- and multi-channel Hot Spot solutions offering bidirectional gigabit-class communication in a room, hall or shopping mall for example.

2.4 Implementation of Li-Fi:

The main components of a simple system based on Li-Fi are:

i) High brightness LED which acts as the communication source

ii) Silicon photodiode which serves as the receiving element

Data from the sender is converted into an intermediate data representation i.e. byte format and then converted into light signals which are emitted by the transmitter. The light signal is received by the photodiode at the receiver side. The reverse process takes place at the destination computer to retrieve the data back from the received light.

LEDs are employed as the light sources. The model transmits digital signal by means of direct modulation of the light. The emitted light is detected by an optical receiver.

Source Computer: Data Reading Module→Data Conversion Module→ Transmitter Module

Destination Computer: Receiver Module → Data Interpretation Module →Data Display (GUI)

The different components serve the following functions:

Data Conversion Module – converts data into bytes so that it can be represented as a digital signal. It can also encrypt the data before conversion.

Transmitter Module – generates the corresponding on-off pattern for the LEDs.

Receiver Module – has a photo diode to detect the on and off states of the LEDs. It captures this sequence and generates the binary sequence of the received signal

Data Interpretation Module – converts data into the original format. If encryption was done, it also performs decryption.

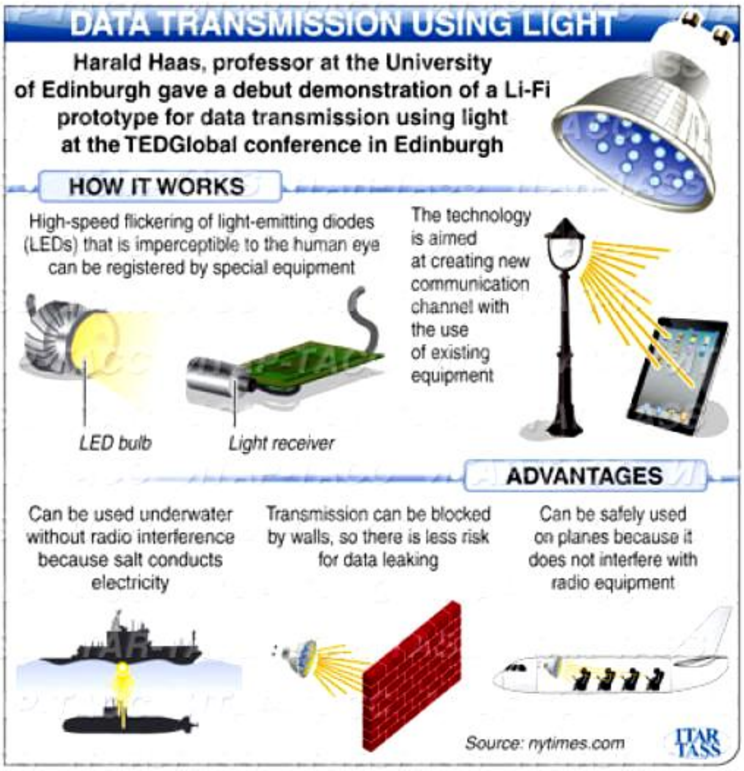

Fig-4: Overview of Li-Fi

III. Applications of Li-Fi

Li-Fi technology can find application in a wide variety of fields. A detailed discussion of its various applications is given below.

(i) Medical and Healthcare

Due to concerns over radiation, operating rooms do not allow Wi-Fi and even though Wi-Fi is in place in several hospitals, interferences from computers and cell phones can block signals from medical and monitoring equipment. Li-Fi solves these problems. Lights are an essential part of operating rooms and Li-Fi can thus be used for modern medical instruments. Moreover, no electromagnetic interference is emitted by Li-Fi and thus it does not interfere with any medical instruments such as MRI scanners.

(ii) Airlines and Aviation

Wi-Fi is often prohibited in aircrafts. However, since aircrafts already contain multiple lights, thus Li-Fi can be used for data transmission.

(iii) Power Plants and Hazardous Environments

Wi-Fi is not suitable for sensitive areas like power plants. However, power plants still require fast and interconnected data systems for monitoring grid intensity, demand, temperature etc. In place of Wi-Fi, Li-Fi can provide safe connectivity throughout the power plant. Li-Fi offers a safe alternative to electromagnetic interference due to radio waves in environments such as petrochemical plants and mines.

(iv) Underwater Explorations and Communications

Remotely operated underwater vehicles or ROVs work well except in situations when the tether is not long enough to fully explore an underwater area or when they get stuck. If instead of the wires, light were used then the ROVs would be freer to explore. With Li-Fi, the headlamps could also then be used to communicate with each other, data processing and reporting findings back to the surface at regular intervals, while also receiving the next batch of instructions. Radio waves cannot be used in water due to strong signal absorption. Acoustic waves have low bandwidth and disrupt marine life. Li-Fi offers a solution for conducting short-range underwater communications.

(v) Traffic

Li-Fi can be used for communications between the LED lights of cars to reduce and prevent traffic accidents. LED headlights and tail-lights are being implemented for different cars. Traffic signals, signs and street lamps are all also transitioning to LED. With these LED lights in place, Li-Fi can be used for effective vehicle-to-vehicle as well as vehicle-to-signal communications. This would of course lead to increased traffic management and safety.

(vi) GigaSpeed Technology

The Li-Fi Consortium provides the fastest wireless data transfer technology presently available. Our current solutions offer effective transmission rates of up to 10 Gbps, allowing a 2 hour HDTV film to be transferred in less than 30 seconds. This can be extended to several 100 Gbps in future versions

(vii) Smart Lighting

Street lamps can in the future be used to provide Li-Fi hotspots and can also be used to control and monitor lighting and data.

(viii) Mobile Connectivity

Laptops, tablets, smart phones and various other mobile devices can interconnect with each other using Li-Fi, much like they interconnect today using Wi-Fi. These short range links provide very high data rates as well as increased security.

(ix) Toys

Several toys consist of LED lights and these can be utilized to implement low-cost communication in order to build interactive toys.

(x) RF Spectrum Relief

Li-Fi networks can be used to relieve the radio spectrum off of excessive capacity demands of cellular networks.

(xi) RF Avoidance

Li-Fi can be used as a solution to any situation in which hypersensitivity to radio frequencies is a problem and radio waves cannot be used for communication or data transfer.

(xii) Indoor Wireless Communication

Li-Fi is very well suited for indoor wireless communication and data transmission. Li-Fi makes use of a free, unlicensed spectrum and is not affected by RF noise. Moreover, most indoor locations would have a sufficient amount of light sources and provide additional security since Li-Fi as previously discussed cannot penetrate through walls.

(xiii) Retail Analytics

Li-Fi can find wide application in retail analytics. Most retail stores consist of a rich lighting environment comprising of abundant sources of light which may be utilized for Li-Fi. Li-Fi could be used to track the behaviour of individual shoppers. Since most customers nowadays possess smartphones, Li-Fi could be used to connect to these smartphones to link up the people, product and purchasing, and thereby greatly simplify the overall shopping process.

(xiv) Casinos

Like retail stores, casinos also have rich lighting environments which could be easily harnessed for Li-Fi, which can find application in the large amount of video monitoring equipment that most casinos employ.

(xv) Hidden Communications

Li-Fi is extremely useful for applications in which communications must be hidden. These involve various military and defense-based communications as well as communications in hospitals.

(xvi) Line of Sight Applications

Li-Fi can also be used in situations where line of sight makes a difference, such as in vehicle to vehicle communication as previously discussed as well as in indoor GPS systems.

(xvii) Spatial Reuse

Li-Fi can act as an alternative in regions with high density wireless communication where 500 or more users may be contending for Wi-Fi. This would lead to low access speeds for the users. Li-Fi can be used to share some of the load of Wi-Fi.

(xviii) Smart Class

Li-Fi can find application in the new smart class technology which is quickly becoming imperative for progressive schools and colleges in the world. Using this technology, teachers show the class a 2D/3D animation on a large screen. They can explain different topics, zoom in to show the important details and freeze and annotate for appropriate emphasis. Through engaging animations, colours and sounds, the teachers gain the full attention of every child in the class. Each child gets visual input on what, where, when and how anything happens and the concepts are well understood. In this technology all the computers are connected to the server using wired LAN technology. The physical transmission medium for wired LAN involves cables, either twisted pair or fiber optics.

However wired LANs pose many disadvantages such as requiring drilling holes in the wall, running cables in lofts, fitting sockets, etc. Hence, the equipment is expensive to install, time consuming to setup, not flexible and requires maintenance by skilled technicians. Implementing smart classes using Li-Fi solves these problems.

Components Used for Li-Fi based Smart Classes:

a. Transmission Source: a high brightness white LED

b. Receiving Element: a silicon photodiode

c. Server: It is a database which stores all the data needed for the smart class.

d. Interactive board: It acts as an input device and monitor, allowing us to control the application by touching the board. It connects with the computer and the projector.

e. Computer: It loads smart class applications and is connected to the interactive board, server and projector

f. Projector: It projects the image on to the interactive board

IV. Some Limitations of Li-Fi

Despite its many advantages, Li-Fi like any other technology also comes with a number of limitations and disadvantages. These are enumerated below:

1) The main problem is that light cannot pass through objects, so if the receiver is inadvertently blocked in any way, then the signal will immediately be cut out. If the light signal is blocked one could switch back over to radio waves.

2) Reliability and network coverage are the major issues to be considered by the companies while providing VLC services. Interference from external light sources like sunlight, normal bulbs; and opaque materials in the path of transmission will cause interruption in the communication.

3) High installation cost of the systems can be complemented by large-scale implementation of VLC though adopting this technology will reduce further operating costs like electricity charges, maintenance charges etc.

4) We still need Wi-Fi and we still need radio frequency cellular systems. You can’t have a light bulb that provides data to a high-speed moving object or to provide data in a remote area where there are trees, walls and obstacles.

V. Conclusion and Future Scope of Li-Fi

Li-Fi is still in its incipient stages and thus offers tremendous scope for future research and innovation. The following is a brief overview of some of the research work being conducted in the field and the future scope for this technology.

Researchers are developing micron sized LEDs which flicker on and off 1000 times faster than larger LEDs. They provide faster data transfer and also take up less space. Moreover, 1000 micron sized LEDs can fit into area required by 1 sq. mm large single LED. A 1 sq. mm sized array of micron sized LEDs could hence communicate 1000×1000 (i.e. a million) times as much information as a single 1mm LED. The Li-Fi Consortium asserts that it is possible to achieve speeds greater than 10Gbps. Researchers at the Heinrich Hertz Institute in Berlin, Germany, have achieved data rates of over 500 megabytes per second using a standard white-light LED.

Harald Haas' group, with researchers from Universities of Oxford, Cambridge, Strathclyde and St. Andrews, are involved in a four-year, £5.8 million project funded by the Engineering and Physical Sciences Research Council. They are researching ultra-parallel VLC, which makes use of multiple colours to offer high-bandwidth linking over few meters. According to Haas, LEDs will evolve to more than just light sources and in the next 25 years, bulbs will have the processing power of modern cellphones. Illumination will only be one of its many purposes.

The Li-Fi Consortium recently demonstrated the use of red, green and blue LEDs as both emitters and photodiodes to detect light. They created a system that could send and receive data at rates of 110 Mbps. With unidirectional transmission, they achieved a rate of 155 Mbps. However, these speeds were achieved with regular LEDs. The Consortium has developed a better LED which can provide data rates close to 4 Gbps while operating only on 5 milli-watts of optical output power and making use of high-bandwidth photodiodes at the receiving end. By enhancing the distance, using a simple lens, they can send data a distance of 10 meters at speeds of 1.1 Gbps.

Mexican company Sisoft and researchers from the Autonomous Technological Institute of Mexico (ITAM) have developed a wireless technology that transmits data through light emitted from LED lamps while simultaneously lighting the room. The team started with audio and cabled up a protoboard table to a smartphone using the 3.5mm audio jack. The table converted the audio signal into a light signal transmitted by an emitter across the spectrum generated by an LED lamp. At the receiver, a receptor in a speaker captured the signal and converted it back to the original audio signal that was then played by the speaker. The principle is similar for wireless internet transmission but it makes use of a receptor designed to be placed above a router. The router contains an LED lamp for transmitting data so that anyone within the halo of the light emitted by the LED will be in transmission range. Sisoft claims to have used this technology to transmit data at 10 Gbps.

More recently, researchers at the University of Oxford employed Li-Fi to attain bi-directional speeds of 224 Gbps. These speeds would allow 18 movies (1.5 GB each) to be downloaded in a single second. The research used specialized broadcast LEDs and receivers which operated with different fields of view as well as bands that impact the data rates. The link operates over a range of about 3 meters at 224 Gbps and 112 Gbps with a wide field of view of 60° and 36° respectively, thereby offering practical room-scale coverage. These speeds far exceed the speeds offered by modern Wi-Fi (about 600 Mbps).

Li-Fi technology thus offers numerous benefits but there are certain barriers that must be overcome before it becomes a ubiquitous part of our lives. Criticisms of Li-Fi include complaints that it cannot work in the dark or if it is raining or foggy, that it is not built into modern computers and questions as to why people should switch to Li-Fi when Wi-Fi could perform similar tasks. However any new technology faces criticisms when first introduced and it will take time before Li-Fi gains broad acceptance. That being said, presently there are many international developers of VLC technologies including Intel, Siemens, CASIO, VLCC, Philips, Fraunhofer, Samsung, ByteLight and the LiFi Consortium. TIME magazine has also named Li-Fi as one of the 50 best inventions of 2011. Li-Fi could ultimately lead to the Internet of Things i.e. all electronic devices being connected to the Internet, with the LEDs on the electronics being used as Internet access points. The Li-Fi market is projected to have an annual growth rate of 82% from 2013 to 2018 and to be worth over $6 billion per year by 2018.

Currently, the University of Edinburgh is immersed in researching Li-Fi to solve many of the problems we have highlighted in this paper. The university has achieved 10 Gbps speed and also demonstrated that line of sight may not be a necessity for Li-Fi transmission. Research is underway on wireless system concepts based on Li-Fi. The university website lists the following projects currently in progress:

1) Optical Multiuser MIMO – It involves exploiting the facts that LEDs offer very directional beams and that intensity modulation (IM) does not suffer from multipath fading. The aim here is to develop new algorithms for multiuser, networked Li-Fi systems

2) Interference Management in Cellular Li-Fi Networks – It is directed towards developing interference cancellation techniques specific to Li-Fi. The project also studies cell cooperation and interference avoidance techniques.

3) The Internet of Things – This is based on the fact that due to the inexpensive nature of photodetectors and LEDs, it is possible to develop small and low-complex transceiver units that allow any LED light to act as a high speed data transmitter.

4) Li-Fi Spatial Modulation – This is a new digital modulation and MIMO technique which allows for highly energy-efficient transmitters since it only needs a single transmitter chain. The project looks into how spatial modulation could be used to support dimming of light in Li-Fi systems and the impact of lenses and polarizers on the performance of optical spatial modulation.

5) Novel Digital Modulation Techniques for Li-Fi – The digital modulation techniques are constrained by the fact that signals must be real valued and positive since Li-Fi uses direct detection and intensity modulation. These constraints cause losses in spectrum and power efficiency. This project attempts to overcome these limitations by developing new Li-Fi modulation techniques such as Orthogonal Frequency Division Multiplexing (OFDM), Carrier-less Amplitude Modulation (CAP) and Pulse-Amplitude Modulation.

6) Self-Powered Li-Fi – This project looks at energy harvesting concepts along with energy-efficient transceiver technologies for Li-Fi systems and requires algorithms of low computational complexity as well as energy efficient techniques for digital modulation. New circuit designs and new synchronization and MAC techniques fall within the scope of this project.

Further research in the field can look into the following issues:

1) Driving illumination grade LEDs at high speed

2) Increasing data rate with parallelism/arrays

3) Achieving low complexity/low cost modulation

4) Overcoming the line of sight constraint

5) Achieving seamless interoperability with other networks

6) Making Li-Fi work in environments with little or no light

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