Chapter 12
LiFi-Based Energy-Efficient Traffic Sensing and Controlling System Management for Smart City Application

Abhinandan Sarkar, Rajdeep Chakraborty, and Hoimanti Dutta

Abstract Alternative research efforts have been conducted for the last few years to overcome the deficit spectrum of electromagnetic waves which can release the network traffic from the saturated radio frequency domain. With some of the culture and development, it can be stated that optical wireless communication can lead to a new spectrum of data sharing. Consumption of data and its usage has increased more than 100 times in the last 10 years. Development of around 80 billion IOT systems has also contributed to the crisis of radio spectrum availability and increased traffic. It is forecasted that by 2022 there will be use of around 50 zettabytes of data, that can be imagined as many bits of stars and planets in the universe. With the recent contribution from researches, a new domain has been termed as visible light communication (VLC) and will reinforce the communication protocol. In this domain, the architectural transformation resulted in light fidelity (Li-Fi), replacing the wireless fidelity (WiFi) with added security and unrestricted bandwidth allocation.

There are 300 Tetra Hz unused bandwidth (1000 times 300 Giga Hz of radio frequency spectrum) available at higher frequencies in the visible light spectrum. LiFi uses the visible light spectrum for communication, which is much faster than radio frequency, and can be easily used in near field communication. Many researches have served with multiple conceptions and misconceptions in this experimental area. The technology is advancing with the speed of its own concept, visible light. Establishing the liable system and computing the data, parametrical diversity is in progress. Professor Harald Haas of Edinburgh University has provided many clear out reach for the proposed system. Many tech-giants have configured their own. But in our daily life, bringing ease to our society has been a concept and dream till now. Converging all the thought at a point with the recent development and implementation, in this chapter we claim to successfully design a light fidelity-based system, which can be used for traffic signal sensing and managing, and it will be energy efficient. As it is studied that LiFi system transmits data through LED and receives through photocell,

A. Sarkar
Shree Ramkrishna Institute of Science and Technology, Kolkata, India

R. Chakraborty (✉) · H. Dutta
Netaji Subhash Engineering College, Kolkata, India
e-mail: rajdeep.chak@gmail.com

P. K. Paul et al. (eds.), *Environmental Informatics*,
https://doi.org/10.1007/978-981-19-2083-7_12

LED is a clear source of energy-efficient output and photocell (solar cells) which absorbs light energy and converts into electrical energy is a proven energy-efficient receptor.

Our system proposes a long-range LED, which transmits light spectrum of over 1.5 km and reflects back after incident on the surface of the vehicles. Solar cells used as receptors of this light beam track the congestion of the beams. The implementation of the transmitter and receiver can be done in affordable and reliable using microcontroller like ATmega 328. The data can be retrieved and processed, and the density of vehicles can be traced, with easy controlling of the traffic signals. With amplification of the incident light beam on solar cells, it can be reused for power support to the circuitry, making it less biasing potential consuming device. The emergency vehicles can also be traced with some deviation of visible light spectrum wavelengths. This design opens up path for many researches on the field of smart city application, environment and its different parameter monitoring systems.

As the system uses LED as a source and solar panel as a receptor, it is very much energy efficient. The solar panel can charge the inbuilt battery itself and can operate in day and night condition. The conventional traffic management system uses mainly camera-oriented system, so this proposed system is quite energy efficient. After feeding the count in the edge level gateways in each of the traffic points, the traffic light may be controlled upon the policy of the city. Thus, this proposed system is quite relevant for smart city applications or smart traffic management system. This proposed system is also cost-effective as it is only using LED, small photocell (here it is solar receptor) and microcontroller ATmega 328 for deployment, and traffic control can be done through edge computing using Raspberry Pi.

Keywords Light fidelity (LiFi) · Energy efficient · Traffic sensing · Traffic controlling · Smart city · IoT

12.1 Introduction

Communication, more precisely development of the communication system or also can be termed as the ways of transferring data, was one of the dominant research cultures from the prehistoric years of human evolution. The species evolved with the symbolic representation on cave walls to communicate with each other. This develop different sound frequencies in various directions. With the separation of the land masses due to the movement of the tectonic plates or the lithosphere area, the culture and vocables became different. Written data transfer came into existence, and with the help of pigeon, it was studied that long distance communication also took place. This whole development happened in the early or medieval era. In the modern times, we can see a rapid growth of communication system, and we had dedicated system for letter distribution and then came the telegrams, trunk calls, computers and land phones. A noticeable time arrived with the invention of wireless communication system and Internet [1]. Life became so easy to connect with distant persons. Another remarkable evolution came with fax machine, where letter can be sent instantly to distant places. With the emergence and development of Internet, email came, land phones got changed to mobile phones, wireless communication developed more with time, and we can see speeding up of data transfer. We can see development of devices; the separated world came to our palm. But with these evolutions, complexity of the systems also increased [2].

When we talk about wireless communication, we mean communication through waves, at a fixed bandwidth and wavelength. Though we are at the verge of expanded communication, we feel unsafe because our life data has come to a risk. Data from different devices get hacked while transferring through unsafe communication ports like WiFi. Though it is studied that data transfer through wireless fidelity technology is quite fast, usage does not limit its risk or insecurity with data transmission and receive. WiFi ports get easily cloned, through which connected devices lose their data. As well we can see that the bandwidth allocation of the propagated wave is too congested, due to which it is becoming slower with days passing. With the development of Internet of Things technology, around 80 million devices are getting connected in the world around. Collision and congestion during data transfer are prevailing problems nowadays.

As a lifesaver, a new technology emerged, invented by Professor Harald Hass of University of Edinburgh, communication through visible light communication. The spectrum frequency ranges from 4.3×10^{14} Hz to 7.5×10^{14} Hz and 400 nm to 800 nm in wavelength [3]. This band is readily available in our indoor environment, which is quite fast and secured for usage. The data is transmitted through the visible light, through a commonly used solid-state device, LED. The question comes why LED? and why cannot we use fluorescents or incandescent light for transmitting data. As we study communication technology, we are clear with the concept of data transmission, and we know that modulation and demodulation of the signal are the spine of the technology. The current intensity of the LED can be easily modulated when compared with other sources. The lifetime of the light emitting diode (LED) is longer, with more efficiency and durability. So what is an LED? LED is a p–n junction semiconductor which emits narrow spectrum light when electric current flows through it, and this can be termed as electroluminescenes [4]. Wavelength of the LED can be determined by its material used to manufacture and the energy gap. For visible light communication (VLC), the use of white light is dominant over others. Some of the unique characteristics of VLC are as follows: the transmission of data is a mathematical representation of channel impulse response or it can be said as transmission matrix [3]. The modulation is on the intensity factor, so phase and frequency are not dependant. The received data is real and positive as the modulation is on the instantaneous power [4]. Another feature is multipath fading, which can be easily omitted in case of transmission through visible light spectrum and use of LED [5]. Reduced cost and security are dominant features for this technology. As visible light does not penetrate through opaque object, we have a considerable parameter of line of sight for data transmission. If we can modulate the signal, decode and transmit in a proper way, this spectrum would prove to be the most safest region of communication. A VLC system can be called as a non-coherent and non-negative signal transmitter.

When we compare radio waves and VLC, both use electromagnetic spectrum for communication but due to the wavelength we know visible light cannot pass any opaque barrier, so data security can be sustained in VLC system. In case of radio waves, though there is loss of signal strength when it passes through thick walls, it passes, and there can be loss of data or theft of it. So in visible light communication, it is restricted to a specified place, range is short, data security is excellent, and speed of data transfer is also good, with reduction of data fading. And as intensity modulation and direct detection method are used to communicate in VLC system, it also gives a considerable advantage over RF. The development of VLC is not to eliminate and reduce the use of radio waves, but to complement its usage [5].

Before going in depth with our proposed model or system, an overall subjective study of the VLC and LiFi systems, its advantage over the contemporary technologies and its various applications need to be studied.

Let us know about the VLC system and its different blocks of functionality. The basic system of the VLC consists of three sections. The transmitter, channel and the receiver make up this three sections. The transmitter block consists of modulator and the transmitting LED; the receiver block consists of a photodiode for capturing the light emitted from the LED, a demodulator; and finally, we get the data. We can also have a cloud data storing facility for remote data access. As our application is based on edge computing, it is beneficial to have remote data serving. The channel in the system is the space between the transmitter and the receiver, which can get affected by interference, noise and attenuation [3]. The VLC system for practical orientation can be single output or multi-output device. But it can be easily seen that, as modulation is dependent on intensity of light, and it can be termed as illumination of that place, or the illumination created by the transmitter, we need enough lexus to transmit data when we are using it for indoor networking. When compared with intensity of fluorescent light or incandescent light, the intensity or power of illumination of LEDs is much more. If we look around us and compare it with our naked eyes also, it can be seen that the illumination created by a 60w fluorescent bulb is much less when compared with using a 18w LED bulb. As discussed earlier, modulation of intensity becomes easy as LED is current-driven semiconductor illuminator. In the VLC system, we can include another block, signal conditioning, that will amplify the signal, reduce noise, filter the signal and provide a more specific and relevant data transmission. In the picture below, we can see a basic block diagram of the VLC system.

In every communication system, there will be losses during data transmission and the received signal carries noise; the signal conditioning block shown in Fig. 12.1 will help in minimizing the noise and other attenuations. Another block that can be added for more optimization is the line decoder, which will maintain the sequence of the data received and also decode the signal in a desirable output.

Let us also understand about the layered architecture of the LiFi system. The diagram of the architecture is given in Fig. 12.2. The basic architectural flow has three layers, physical layer, MAC layer and the application layer. The physical layer

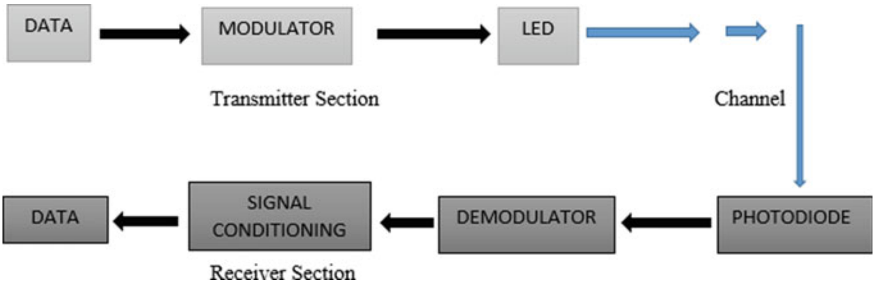

Fig. 12.1 Basic block diagram of a VLC system

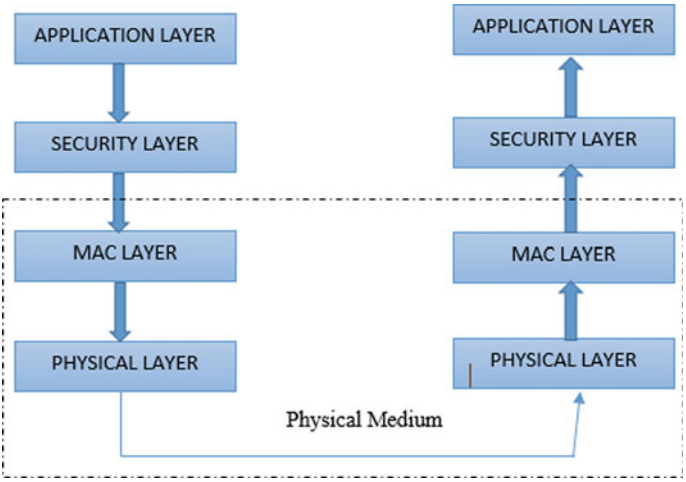

Fig. 12.2 Layered architecture of LiFi system [7]

connects between the device and the medium, and in simple words, it acts as the transmitter and the receiver of the LiFi system. Different modulation techniques are followed in different systems, and according to the layer modularity and construction, mainly it is studied that on–off keying, orthogonal frequency division multiplexing and quadrature amplitude modulation, colour shift keying and pulse modulation techniques are used. The medium access control layer is concerned with visibility support, dimming and mobility support, VPAN disassociation and networking beacon generation for coordinating device. As data security is one of the important aspects in today's communication ports, we propose another layer in the architecture for security purpose, and lastly, we have the application layer. So proposing three important layer, physical layer, MAC layer and the security layer or can be said as added security layer [6].

As stated above about the modulation technique, let us know in brief about the mentioned techniques, for the better understanding of the proposed concept. Starting

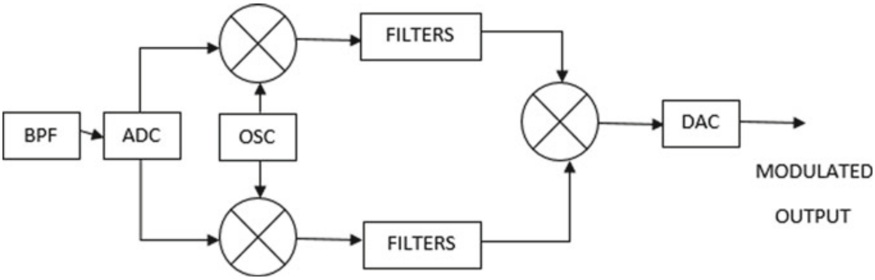

Fig. 12.3 Building blocks of QAM

with orthogonal frequency division multiplexing (OFDM), it is mainly done when conventional serial modulation schemes are used like quadrature amplitude modulation (QAM). Combining OFDM with QAM minimizes the inter-symbol interference. Another advantage of using OFDM is that the signal complexity in transmitter and receiver is easily transferred to digital domain from analogue domain. The implementation of OFDM is quite simple, data is transmitted in multiple frequencies on parallel path, and hence, the symbol period tends to be much elongated compared to the serial system but with same data rate. So, the effect of inter-symbol interference is maximum to 1 symbol, and hence, equalisation is achieved [8]. In a QAM system, there is a mixing of two amplitude modulated signals, and hence, it increases effective bandwidth. For a better-optimized interference free signal, less noisy signal OFDM-QAM technique is widely used in multiple wireless communication system [9]. Figure 12.3 shows a basic QAM system.

Another commonly used modulation scheme is on–off keying (OOK). Though there are limitations like interference and spectral inefficiency, we achieve enhanced energy per bit and lower power levels than 802.15.4 [10]. In this scheme, the on state is represented with 1 and 0 is used to represent off state, but the LED is not completely off, and it is dimmed to reduce the intensity level and trigger the off state [7].

Pulse modulation (PM) technique and colour shift keying (CSK) are other few generally used modulation schemes. As previously discussed, for LiFi, the intensity of light or modulation of it is the working factor, and we do not need to modulate the frequency or the phase, so in case of pulse modulation schemes, pulse amplitude modulation or pulse width modulation is used to vary the intensity according to the data bits [11]. By the name colour shift keying, we can identify the theory behind CSK, that modulation is done by variance of 3 LED, red green and blue, and it is dependent on the colour space chromaticity diagram [7].

Though there are misconceptions for LiFi as a sustainable communication system, like LiFi is line of sight scheme, it cannot be dimmed, it does not work in sunlight, it flickers a lot, and it is for downlink only, these limitations can be recovered by using variety of modulation techniques, among the above stated few like OFDM intensity modulations and uni-polar OFDM [12].

LiFi with varied applications, in different domain, comes encapsulated with new age computing techniques and gives a new path for data communication, with very little power consumption and simplified networking theories. Our article concept is based on such an application of visible light, where it is established in the centre of a multi-junction road. The LED is fixed in this way that it does not hit the driver sight, but is long range enough (around 1.5 km) to travel and incident on vehicles at an angle, so that it reflects back to origin, to get absorbed and detected by the implemented solar panels or photodiodes at the junction. The intensity of the reflected ray produces a current, more the intensity of reflection, more the current generation, and we can predict this as more traffic in that path. If there was less traffic, the pitch used in making roads would not reflect back much light, as maximum of it will get absorbed by the deep ash colour of it. The reflected ray would come from the shiny metallic bodies of the cars or vehicles. To implement this project, we tend to get through some minute details, how the circuit gets its power in the middle of the road? Who gets the data? How it can be fetched from remote places? The sunlight during the day will interfere with LEDs, how to optimise the concept during day time? How to process the signal against bright sunlight? Will there be flickering with ageing of the light? Is it cost-efficient? How to implement edge computing techniques on a lamp post? Will the design prioritize emergency vehicles? All this queries will be discussed in our methodology section to draw the concept clear to the expected readers. Section 12.1 discusses the related studies, Sect. 12.2 gives the detailed methodology, and Sect. 12.3 draws the conclusion. References are listed at last.

12.2 Related Studies

In this section of the article, we discuss about some of the related works in this field. This section will provide a more insight to the design concept.

The technology got its inception in 1990, from Japan, Germany and Korea. In [13], they discuss about the scarcity of radio waves, its capacity, congestion, efficiency, availability and security. The deficiency in radio waves gives an alternate solution of light fidelity. The chapter proposes in establishing a LiFi-based system to prioritize the vehicles and differ the signals automatically. As traffic light uses LED, establishing such a system would not be of great challenge. Emergency vehicles can also transmit the signal of priority through the on top mounted signal lights, which makes the traffic movement easy and broadcasts the signals or delays up ahead. The chapter also shares some applications of LiFi in different fields, like airways, medicals, underwater vehicles and hotspots.

The article [14] states the visible light communication to be bi-directional, that it can be used for both uplink and downlink. The connectivity is in large area, with high speed data transfer and security. The articles propose a system that has a LiFi-enabled taillight and headlight of vehicles and also the traffic signals. This will help in road safety and traffic management by establishing a vehicle-to-vehicle communication drive, hence reducing road accidents and optimizing the traffic signals.

Article [15] also describes the LiFi system like the previous article, but the theory of the chapter is based on the different technical standards and modulation techniques used and is going to be used in near future for establishing a LiFi domain for traffic management. It shares the use of RFID in traffic management with its advantages and disadvantages with the future of LiFi and how much workable it is going to become.

In articles [16] and [17], the proposed system is of vehicle-to-vehicle communication, where the head lights are made as LiFi transmitter and tail lights are made as LiFi receiver. This concept helps in alerting the traffic signal about emergency vehicles, and once the signal is received, immediately the signal turns green, decreasing the wait time of the vehicle in congested roads. This V2V communication system helps in communicating between the vehicles and sharing required information in the road.

12.3 Methodology

In this section, we discuss about the detailed description of the project. Till now, we have discussed in detail about the visible light communication, the backbone of our design. We have said how VLC works and what are the different modulation schemes used to transmit data. Though there was some shortcomings and misconceptions about LiFi, it can also be sorted using specific multiplexing and modulation techniques.

Our design is a complement to the latest technologies used in traffic control. Today, we have a pre-defined counter, that defines how much a car has to wait for the green signal. We have camera which is very costly, and it monitors the traffic inflow and outflow, the density of vehicles and traffic rules. But it has a problem that it is not remotely monitored, the traffic outpost is very near, and maximum number of cameras are wired to the display devices. In metro cities, some WiFi-enabled cameras are established for a certain distant monitoring of the vehicles, but are too costly. It has been noticed that emergency vehicles like ambulance and fire brigade vehicles do not get enough space in tight traffic to go out. Once a road becomes congested, it has to be immediately evacuated, to maintain a smooth traffic. When manual control or fixed timing is set, the traffic cannot be smoothen immediately. With costly visual capturing devices, it is not affordable to establish it in every corner of the city or town.

Throwing some light on another aspect, remote monitoring and automatic monitoring of traffic become difficult when WiFi devices are not connected. We intend to provide a one stop solution to the issues arising in everyday life. With the implementation of edge computing, the data is processed in real time on the location and the traffic is monitored.

As previously discussed, a VLC transmitter is a LED, and the receptor is a solar cell/panel or photodiodes. The cost is very less in comparison to the camera vision. We need a microcontroller to process the data. We prefer using Arduino UNO developmental board, which has AtMega328 microcontroller, inbuilt ADC to connect

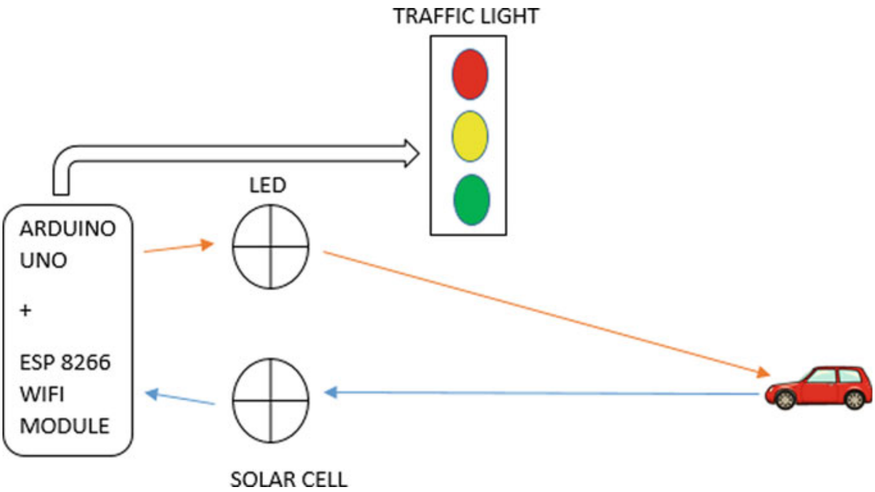

Fig. 12.4 Basic concept of the project

digital and analogue devices. It also has a embedded crystal oscillator to trigger the machine states for proper timed operation. The LED and the solar cell are attached to the board for light transmission, receiving of reflected back rays, processing of the intensity received and taking action on the traffic signal. We can connect a ESP8266 Arduino compatible WiFi module to upload the traffic data on the cloud, which will give a further detailed study of the traffic timings and controls and from where the characteristic of the solar cell can also be studied. The figure below shows the basic concept of the project.

As it can be seen in the basic block in Fig. 12.4, Arduino board is connected to the LED, and the intensity of the light in LED is modulated by the Arduino. LED transmits the light towards the road, incidence on the cars, gets reflected back towards the solar cell. The cell captures the light and produces current accordingly. More the intensity of light, more will be the current electricity generation. This generation is in analogue form, and the ADC converts the data into digital bits. More the intensity, more number of higher bits flow in the processor. Once the processor fetches the data after processing, if found to be a constant flow of higher bits, it can be followed as congested road, or still traffic. Immediately, the processor sends signal to the traffic light to change from red signal to green signal. So that heavy traffic is minimized in that road, giving a smooth movement of vehicles. In Fig. 12.5, we can see the analogue or continuous change of current with the flow of different vehicles on the road. There is a fall in the level with minimum vehicles, and there is rise in the signal with increasing vehicles. It can also be seen a approximately constant signal when the signal is red and the vehicles are still, giving a brief insight of a congested road. This signal is converted into digital signal by feeding it to the analogue to digital converter of the UNO board.

The relationship between light intensity and current can be given as:

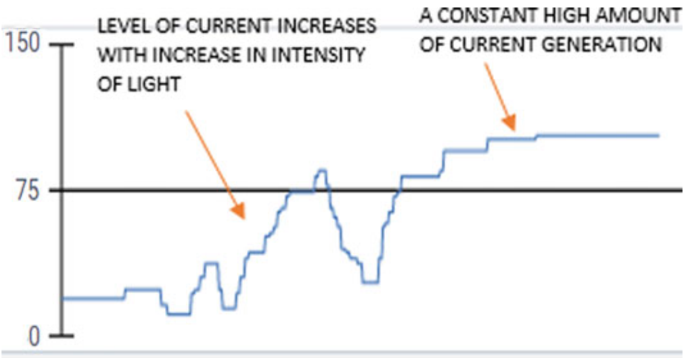

Fig. 12.5 Variation of solar cell signal (current) with light intensity

$$L_{\text{intensity}} \propto I_{\text{generation}} \tag{12.1}$$

From Eq. (12.1), we can understand that as the intensity of light increases, the flow of electron in the circuit increases because more photons strike the panel, so more generation of current. It can also be traced about the congestion of road, with increase in the current flow from the solar cell. A digital output of the solar cell is shown in Fig. 12.6.

If we notice the curve of Fig. 12.6, it shows a square wave. From the curve, it is visualized that the bit pattern is tentatively 11,110,011,111,111 and so on; when the current generation is not above the threshold value or the margin, the Arduino processes the data as 0; as it crosses the threshold value, the ADC gives 1 as output; and accordingly, the traffic signals are manipulated automatically. With connection of ESP 8266 WiFi module with Arduino, the whole data and its variation can be uploaded in the cloud storage for remote accessing and post-processing of other parameters.

In the introduction section, we have raised some questions, some of the queries we have already discussed, and in this paragraph, we will discuss the rest in brief. As

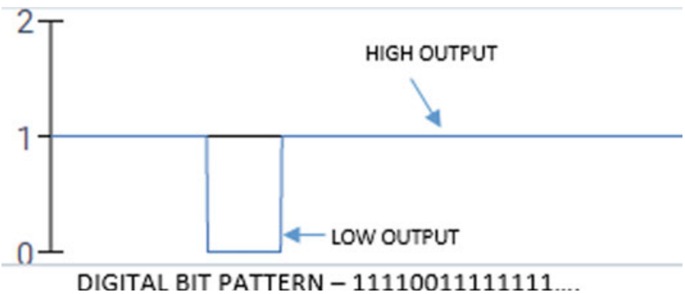

Fig. 12.6 Digital output of Solar cell

we see, we have a solar cell or panel attached as receptor, and the battery which is providing the power will get charged from the current generated in the cell. During daytime, due to the presence of sunlight, the battery will get charged, which will continue to supply power during the night time, with a small amount of charging from the light intensity during night. Though there will be sunlight with OFDM-QAM modulation techniques, we can reduce the interference or minimize it to such level that we get a prominent data. With implementation of solid-state device, the system does not get affected by flickering with ageing. And the system can prioritize emergency vehicles, as emergency vehicles have signal lights on top; with colour detection schemes, we can detect the wavelength and frequency of the red light; and special action can be taken to bypass the emergency vehicles.

The processing becomes challenging when we come across a junction point like 4 points or 5 points. Detecting the prominent congestion can incur a little delay of few seconds. But comparing with a camera system, it is way cheaper and a better way of data communication, as it does not use radio waves for this process. When we make the hybrid model [18] for cloud interfacing, we require a WiFi connected to the LiFi system for continuous updation. The graphical representation Fig. 12.7 below shows the output of receptor for a 4-point junction. We will also highlight the decision-making process of the microcontroller against the signal generated.

From the above representation, we see the variation of the current in the solar panels due to the different intensity of light at the 4 signal points. We assume all the four signals are red, so the signal becomes constant after a certain time, and we will see which signal will be green first. And the sample is taken for few minutes after the signals turn red. If we see for lane 3, the signal value is very low near about 20–50. In lane 4, the value is near about 190–200, so we can predict that the lane is quite full. The value of lane 2 is little bit higher than lane 4, just crossing 200, so we can say lane 2 will be green before lane 4 at this instant and then lane 3. Now, from lane 1, the value is reaching to 350–390, and when compared to the other lanes, it is highly congested. So lane 1 will get the green signal first and then lane 2 followed by

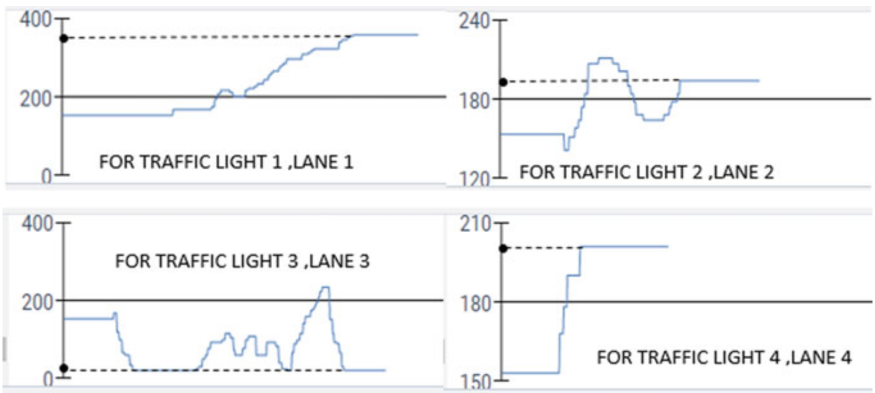

Fig. 12.7 Signal variation at different points

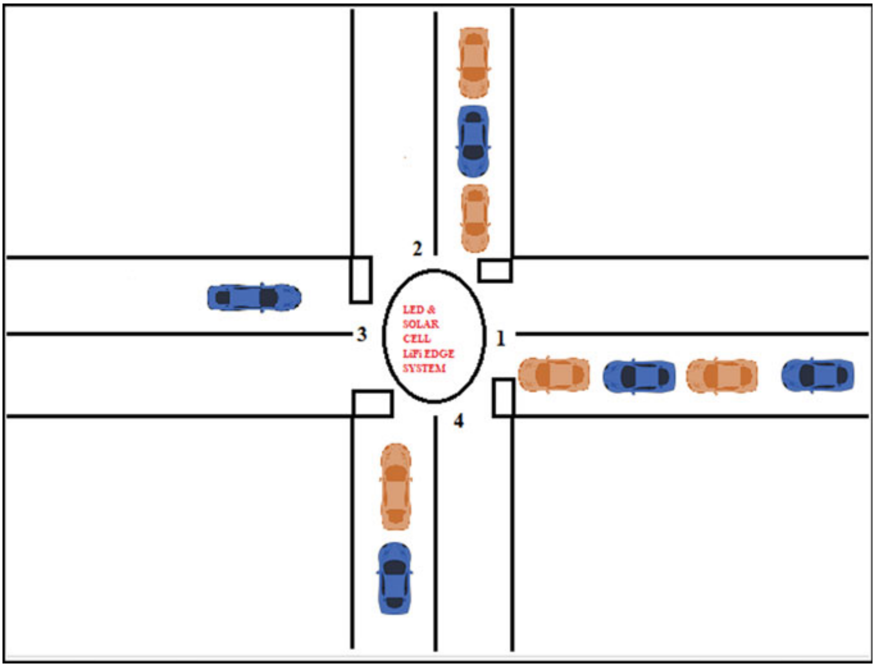

Fig. 12.8 Structural concept of the traffic management system

lane 4 and lane 3. After analysing the data from the graph, now we can visualize the system established on the 4-point traffic crossing. In Fig. 12.8, we give the structural concept of the traffic management system.

In the above figure, we have shown the deployment format of the system, and the figure also relates to the graphical outputs in Fig. 12.7. The lanes have been marked accordingly, and the density of vehicles is also picturized for a better understanding. As defined in the previous paragraph, the signalling will work from lane 1 and then 2 followed by lane 4 and lane 3. The LiFi system will be mounted on a tall tower in the centre of the junction, with four sensor-receptor system to get data from four directions. We can use only one Arduino UNO as it has enough ports to interface with four input–output devices. Though it seems that there may be lag in data fetching, but giving a appropriate delay with the four processes, the Arduino gets enough space for the previous execution cycle to get complete. So data over-writing or lagging in delivering the output can be minimized. The microcontroller compares the signal generated in the receptors and gives the signal change command towards the most congested lane. Giving it a Go! Signal for the lane to become decently filled and moving towards the next highest signal and so on. Once it executes the signal from all the panels, it waits for the next congestion signal to act upon. There may be a situation where, once the traffic signal goes red, the vehicles get packed up, while the other lanes are moving, so the controller checks the signal for few seconds, till it gets a good intensity on the panel and executes the signal on that lane. The whole process can be defined in multiple ways the programmers wants it to be.

So from this design of the LiFi system, and applying some basic calculations, we can predict the congestion of traffic on the road and can establish an automatic traffic management system giving a path for development in smart cities.

12.4 Conclusion

Though the inception is studied to be in 1990 [13], but the practical demonstration of the technology was done in 2011, in Ted talk series by Professor Harald Haas, he demonstrated the working capabilities of LiFi. He also showed how in foggy weather the data will get transmitted, and he showed a transmission of video through a led lamp, which gets played in the receiving side laptop. He proves the transmission by blocking the path of visible light. Many researches and development are in process for the light fidelity. Many applications are developed. We propose for one of the application of visible light data transfer concept for traffic management. The article describes about the advantage of LiFi over WiFi. We can use the techniques to get the appropriate data. We describe how intensity of light affects the current generation in the solar cells, thus varying the signals in the microcontroller board. There are multiple future scopes from this article for further development, like pedestrian management, accident monitoring and alarming system and data communication between vehicles. Attaching with GSM module, we can predict the location of the vehicle giving a complementing solution to GPS. Thus, we can conclude that light fidelity will take over the new generation of industries, transportation, smart cities and many more real-world applications.

References

1. Khandal, D., & Jain, S. (2014). Li-fi (light fidelity): The future technology in wireless communication. *International Journal of Information & Computation Technology, 4*(16), 1687–1694.
2. Leydesdorff, L. (1994, March 21). The evolution of communication systems. The evolution of communication systems. *International Journal of Systems Research and Information Science, 6*, 219–230. Available at SSRN: https://ssrn.com/abstract=2236680
3. Webster, J. G., Ndjiongue, A. R., Ferreira, H. C., & Ngatched, T. M. N. (2015). Visible light communications (VLC) technology. In J. G. Webster (Ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. https://doi.org/10.1002/047134608X.W8267
4. Gancarz, J., Elgala, H., & Little, T. D. C. (2013). Impact of lighting requirements on VLC systems. *IEEE Communications Magazine, 51*(12), 34–41. https://doi.org/10.1109/MCOM.2013.6685755
5. Burchardt, H., Serafimovski, N., Tsonev, D., Videv, S., & Haas, H. (2014). VLC: Beyond point-to-point communication. *IEEE Communications Magazine, 52*(7), 98–105. https://doi.org/10.1109/MCOM.2014.6852089

6. Harald, H. (2018). LiFi is a paradigm-shifting 5G technology. *Reviews in Physics, 3*, 26–31. ISSN 2405-4283, https://doi.org/10.1016/j.revip.2017.10.001
7. Ullah Khan, L. (2017). Visible light communication: Applications, architecture, standardization and research challenges. *Digital Communications and Networks, 3*(2), 78–88, ISSN 2352-8648, https://doi.org/10.1016/j.dcan.2016.07.004
8. Armstrong, J. (2009). OFDM for optical communications. *Journal of Lightwave Technology, 27*(3), 189–204. doi: https://doi.org/10.1109/JLT.2008.2010061
9. Li, X. (2008). Simulink-based simulation of quadrature amplitude modulation (QAM) system. In *Proceedings of the 2008 IAJC-IJME International Conference.*
10. Daly, D. C., & Chandrakasan, A. P. (2007). An energy-efficient OOK transceiver for wireless sensor networks. *IEEE Journal of Solid-State Circuits, 42*(5), 1003–1011. https://doi.org/10.1109/JSSC.2007.894323
11. Deloraine, E. M. (1949). Pulse modulation. *Proceedings of the IRE, 37*(6), 702–705. https://doi.org/10.1109/JRPROC.1949.233950
12. Haas, H. (2016). LiFi: Conceptions, misconceptions and opportunities. *IEEE Photonics Conference (IPC), 2016*, 680–681. https://doi.org/10.1109/IPCon.2016.7831279
13. Kalaiselvi, V. K. G., Sangavi, A., & Dhivya. (2017). Li-Fi technology in traffic light. In *2017 2nd International Conference on Computing and Communications Technologies (ICCCT)*, 2017, pp. 404–407. doi: https://doi.org/10.1109/ICCCT2.2017.7972307
14. Yeasmin, N., Zaman, R., & Mouri, I. J. (2016). Traffic control management and road safety using vehicle to vehicle data transmission based on Li-Fi technology. *International Journal of Computer Science, Engineering and Information Technology, 6*(3/4), 1–7.
15. Al_Barazanchi, I., Sahy, S. A., & Jaaz, Z. A. (2021, February). Traffic Management with Deployment of Li-Fi Technology. In *Journal of Physics: Conference Series* (Vol. 1804, No. 1, p. 012141). IOP Publishing.
16. Shanmughasundaram, R., Vadanan, S. P., & Dharmarajan, V. (2018, February). Li-Fi based automatic traffic signal control for emergency vehicles. In *2018 Second International Conference on Advances in Electronics, Computers and Communications (ICAECC)* (pp. 1–5). IEEE.
17. Mugunthan, S. R. (2020). Concept of Li-Fi on smart communication between vehicles and traffic signals. *Journal: Journal of Ubiquitous Computing and Communication Technologies*, *2*, 59–69.
18. Abuella, H., et al. (2021). Hybrid RF/VLC systems: A comprehensive survey on network topologies, performance analyses, applications, and future directions. *IEEE Access, 9*, 160402–160436. https://doi.org/10.1109/ACCESS.2021.3129154
19. Albraheem, L. I., Alhudaithy, L. H., Aljaser, A. A., Aldhafian, M. R., & Bahliwah, G. M. (2018). Toward designing a Li-Fi-based hierarchical IoT architecture. *IEEE Access, 6*, 40811–40825. https://doi.org/10.1109/ACCESS.2018.2857627