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Visible Light Energy Harvesting in Modern Communication Systems

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***Abstract*—The increased data traffic in Radio Frequency (RF) wireless communication has put tremendous pressure on already scarce bandwidth in the RF spectrum. The energy efficiency and importance of sustainable energy sources for the internet of things (IoT) devices owing to its large energy consumption is also a major concern in wireless communication. A major breakthrough to combat this challenge is RF energy harvesting (RF-EH) technology where the energy content of ambient radio waves and radiations from base stations are exploited for EH. The wireless power transfer (WPT) and simultaneous wireless information and power transfer (SWIPT) are prominent schemes in RF-EH. However, the exponential growth of IoT with more than billion connected devices and several zettabytes of data demand predicted by 2020 is going to render RF spectrum insufficient. This alarming threat has led to deployment of visible light communication (VLC). Deployment of Light Fidelity (LiFi), an extension of VLC, is a major innovation towards combating the challenges presented in traditional communication setup. This paper presents the prospect of extending VLC application in three folds: illumination, communication and EH from the unlicensed free visible spectrum by light energy harvesting. The potential of visible light (VL) as an alternative candidate for energy source in wireless networks is presented with a case study predicting scenario of EH integrated into VLC. This presents the prospect of green wireless communication, fulfilling the objective of future communication, i.e. high speed data rate, energy efficient, sustainable wireless communications.**

***Index Terms*—Visible Light Communication, 5G communications, simultaneous wireless information and power transfer, Visible Light Energy Harvesting.**

I. Introduction

The evolution of communication technology has played a greater role in connecting the people. As in [1], a new mobile generation has appeared approximately every 10 years since the first 1G system in 1982. Ever since the launch of 4G in 2012, fifth generation (5G) Wireless Networks have been conceptualized and expected for implementation in the early 2020s [1]. Efficient wireless sensor networks for faster information transmission will be the significance of 5G mobile communication. The cluster of sensor nodes automatically forms sensor networks, enabling the cooperative information transmission and each node consumes its own energy [2]. It is challenging to replenish the batteries, particularly in harsh network conditions and not cost effective as well. On the other hand, the efficiency of network in data communication is compromised due to battery outage in nodes. Therefore, an alternative mechanism to energies the nodes and efficient usage of node's energy has become necessary to prolong the lifetime of wireless network [2] [3] [4].

The need for increasing the data rate and energy efficient network has given way to 5G mobile communication systems, an enhancement of shortcomings in 4G. In addition to increased data rate and lower energy consumption, power sustainability is critically looked into to ensure 5G as the Green Mobile Communication Networks [5]. Enhancing the quality of service (QoS), guaranteed packet transmission with minimum delay, high throughput, low outage probability and high energy efficiency in the 5G communication system are the priorities [6] [7] [8].

Energy harvesting (EH) technology is a promising approach to prolong the network lifetime [8] [2] [3]. The EH technology has come into prominence and harvesting from ambient Radio Frequency (RF) has attracted lots of attention [9]. The ability to harvest RF energy from ambient or dedicated sources enable wireless charging of low power devices, eliminating the requirement of battery replacement. Therefore, RF signals are seen as alternative and sustainable source of energy to engineer the power requirement for wireless communications. The wireless power transfer (WPT) schemes are devised and analyzed [10] [11] [12] where electrical energy produced from a power source i.e. RF signals are transmitted without using interconnections to electrical components [13]. The need for wireless power transmission for energy sustainability in the network and uninterrupted wireless information transmission has led to emergence of simultaneous wireless information and power transfer (SWIPT) schemes. A fundamental concept of SWIPT is already used in applications like RF identification (RFID) and power line communications [13]. The SWIPT technology is expected to gain a tremendous amount of spectral efficiency, time delay, energy consumption and interference management.

However, bandwidth limitation and drawbacks of RF communication systems force researchers to search for new com-

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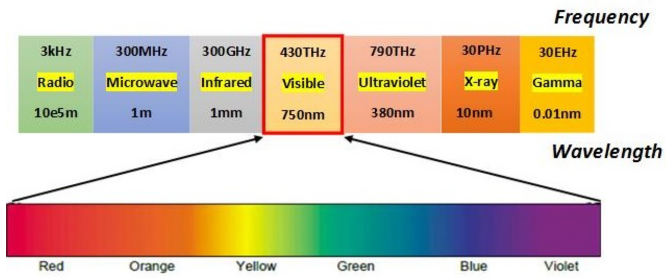

Fig. 1. Visible Light Communication Frequency Spectrum

munication technologies. The usage of visible light (VL) spectrum for communication as an alternative for RF communication is extensively investigated by research community lately [14].

In this article, we provide an overview of VLC as a potential candidate for EH in 5G communication networks. In this work we present concrete possibilities for the advancement of Visible Light Energy Harvesting (VL-EH) in 5G. The review begins with a brief explanation of VLC. Then we discuss VL as an energy source by highlighting its advantages over existing RF-EH. The prospect of VL-EH implementation is further explained using a case study of a smart room. Finally the challenges and future recommendations are provided towards integration of VL-EH in existing RF EH techniques in 5G communication.

II. Visible Light Communication

Alexander Graham Bell in 1880 practically demonstrated VLC with his photophone and declared as "the greatest invention [I have] ever made than telephone" [15] [16]. When the RF communication is under the tremendous pressure on handling data traffic, the VL in electromagnetic (EM) spectrum in Fig.1 provides 100s of bandwidth in $terahertz$ (430THz to 790THz) with wavelength from 750-380 nm free. This untapped unregulated free spectrum provides huge opportunity to manage the future communication problems [16]. The visible spectrum offers 10000 times higher spectrum than RF spectrum with additional advantages such as almost zero interference as light cannot penetrate through opaque bodies and health risks which otherwise is associated with RF radiation [15] [17].

The recent widespread use of solid state lighting (SSL) systems such as Light Emitting Diode (LED) replacing the conventional luminaries towards low power and efficient lighting systems has contributed to the emergence of VLC in wireless communication fields [18]. It was projected the LEDs would provide as high as 113 lumens/watt in 2015 and is expected to be further enhanced by around 200 lumens/watt by the year 2020 [17]. Traditionally VL were used for illumination alone but its potential in particular to wireless communication is realized lately. In VLC light sources serves two purposes i.e. illumination and data communication. This work is extensively done by Professor Harald Haas at pureLiFi [17] [15].

The varying intensity of LED light sources/transmitter is modulated in such a way generating millions of data ('1' or '0' /ON and OFF) where the flickering of lights is imperceptible to the human eyes [17]. The light signals are demodulated back into electrical current by photosensitive detector called VLC receiver [18] [15]. The Fig.2 represents data transmission achieved in VLC technology.

It has the potential of providing data speed of 4Gbps in special and 1Gbps in normal setting thereby motivating the works in [17] [18] [19]. Light Fidelity (Li-Fi) is not a theoretical concept anymore but at real-world deployment [17] ensuring the effective usage of luminaries for dual purpose i.e. illumination and data communication [15] [16] [19]. The VLCs prospect of application in RF prohibited networks [20] and possibility of building on the existing lighting infrastructures makes it even more exciting. Light cannot penetrate through opaque/ walls making the network more secure and resistant to interference as compared to RF signals [21]. A comparison between RF and VLC is mentioned in the TABLE I.

A. Visible Light as a Source

The EM radiation available all around are the energy source taking many forms. The ambient VL source available in abundance in buildings and smart cities [44] are good source of energy that can be harvested to support the energy requirement in wireless communication. The photon energy content in each VL in VL spectrum is related by

$$E = hf, \tag{1}$$

where h is constant (Planck's constant). It shows that as wavelength decreases, frequency increases, so does the energy that carry. The photon energy for each coloured light ranges from red with 1.65 to 2.00 eV to violet with 2.75 to 3.26 eV. Therefore, violet ray with $380 - 450$ nm wavelength and $668-789$ THz frequency in Fig.1 is known for its most energy contain. Also the conversion of monochromatic light at 633 nm wavelength to electricity is shown to be upto 9% efficient with output potentials of 0.4V while conversion of solar energy to electricity is estimated to be 2% efficient [45]. The photovoltaic (PV) solar cells are the most common device for converting light into electricity which are in varieties suitable for differing light sources. The radiant energy (RE) in EM radiation concentrated in the visible spectrum transfers energy through space. Fig.4 is considered where a wireless device of differential cross-sectional area dA is illuminated by a light source of radiant flux (ϕ) forming an angle (θ) between the ray and surface normal at the point. The amount of radiant energy (spectral radiant energy) per unit wavelength interval at particular wavelength is obtained as

$$Q_\lambda = \frac{dQ}{d\lambda}, \tag{2}$$

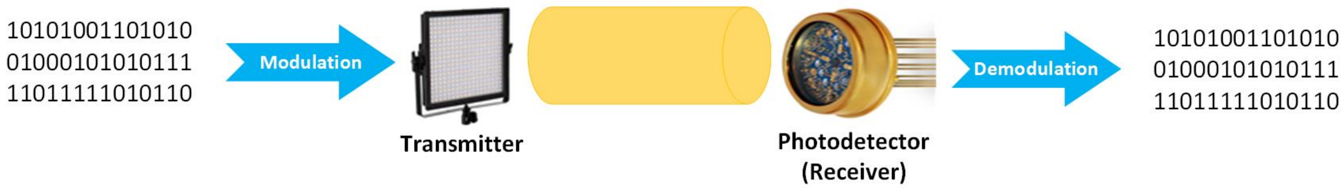

Fig. 2. Concept of VLC

TABLE I
COMPARITIVE STUDY BETWEEN VISIBLE LIGHT COMMUNICATION AND RF COMMUNICATION

Specifics	VLC	RF	Reference
Electromagnetic (EM) Spectrum	Spectrum is in THz, 10000 times more bandwidth than Radio wave spectrum	Spectrum in GHz with bandwidth below 10 GHz is insufficient to meet exponential growth in demand	[22] [23] [24]
Medium for transferring data	High speed Varying light intensity from LED luminaire transmits data	Radio waves transmits data with the help of WiFi router	[24] [25]
Data transfer speed	Can achieve transfer speed greater than 1 $Gbps$ (33 x Wi-Fi considering fastest WiFi network achieved is 30 $Mbps$ in South Koreas) in normal network	Data transfer achieved is limited to about 150 $Mbps$	[26] [27]
Network topology	Beyond Point to point	Point to point	[28] [29] [30]
Security	More secure, light carrying data cannot penetrate walls or any other opaque materials	Vulnerable to intrusion as radio waves can penetrate walls	[31] [32] [33] [34] [35]
Issue of Interference	Minimum network interference as data transmission is concentrated within the beam of light	Numerous access points (routers) in Wi-Fi setup actually degrades the quality of network	[36] [37]
Power efficiency and ease of deployment	Can be deployed in energy efficient, low power consuming existing LEDs infrastructure enabling the feasibility for Internet Anywhere (street lamps, vehicle lights towards internet in footpaths, roads, underwater communication etc)	Base stations consumes huge power and costly for deployment everywhere	[38] [39] [40]
Health safety and management	Safe for human health therefore, usable in WiFi prohibited zones	Radio waves can penetrate human bodies, hence prohibited in hospitals, industries and aircrafts and medical devices	[41] [42]
Network coverage	Short range Line of Sight (LoS) data communication	About 32 meters (WLAN 802.11b/11g), vary based on transmit power and antenna type	[17] [29] [43]
Available standards	Deployed yet it is in developing stage without proper framework	Advanced stage covering worldwide	[22] [43]

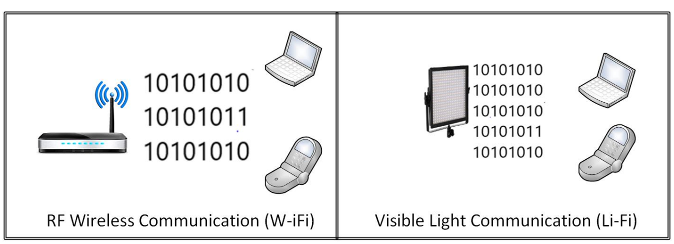

Fig. 3. Representing scenario of RF vs VLC

where Q is radiant energy in joules. The radiant power also called radiant flux from the emitted illumination is expressed in terms of radiant energy as

$$\phi = \frac{dQ}{dt}, \tag{3}$$

where t is time. The irradiance i.e. the radiant flux (power) received by a surface per unit area is expressed as

$$E = \frac{d\phi}{dA}. \tag{4}$$

On reaching the light on a surface, the radiant flux arrived on the surface is the spectral irradiance expressed by

$$E_\lambda = \frac{dE}{d\lambda}. \tag{5}$$

The infinitesimal amount of radiant flux contained in the receiving light ray is the radiance. It is expressed as

$$L = \frac{d^2\phi}{[dA(d\omega \cos\theta)]}. \tag{6}$$

The amount of energy that can be received by a surface also depend on the distance of device on the surface and intensity of radiant flux intercepting at an angle θ on the differential cross-sectional area of device surface. This is termed as radiant intensity expressed as

$$E = \frac{I \cos\theta}{d^2}, \tag{7}$$

giving a radiance of

$$L = \frac{dI}{(dA \cos\theta)}, \tag{8}$$

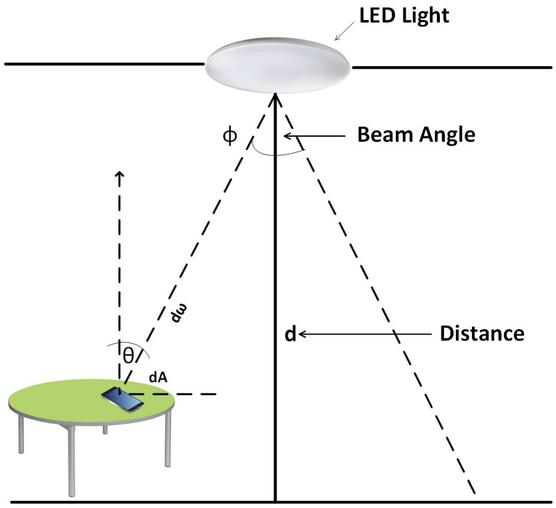

Fig. 4. A wireless device of differential cross-sectional area dA is illuminated by light source of radiant flux ϕ forming an angle θ between the ray and the surface normal at the point.

where I is the intensity of the light source, d is the distance from the source to the surface dA and $d\omega$ is the differential solid angle formed by radiant flux on arriving on the surface. The equations 2-8 reproduced from [46] describes the energy contain in VL. This presents good prospect to exploit the available light source as an alternative source of energy particularly for the power requirement in wireless devices in the network.

B. Related work on Energy Harvesting in Visible Light Communication

The VL in EM radiation has the potential to achieve two important milestones in the era of demand for high data rate and energy efficient operation of wireless network. The VLC already deployed in the form of LiFi serves two purposes: efficient illumination and high speed data communication. The VLC deployment can be further enhanced towards deriving another milestone, the EH from ambient light sources, particularly from artificial electrical light sources. This would ensure the power sustainability where devices' battery gets charged simultaneously while it carries information and provide illumination. The availability of different range of photo-detectors in solar cells makes the EH process more relevant for varieties of light sources of varying intensities. In [44] investigated the power output achievable from four types of solar cells under three illumination sources: incandescent lamps, compact fluorescent lamp (CFL) and LED. It is found in [44] the output power density reduces drastically on changing the illumination sources from incandescent to CFL to LEDs respectively. Also solar cell based harvester performs adequately with specific light source but it is insufficient if light sources are changed. The energy efficient lighting systems with emergence of LED lighting systems with its capacity to save energy upto 85% [44] also shows EH prospect in VLC. Exploiting the advantages of VLC to be integrated with RF communication for better network accessibility has become the emerging trend of research interest. The authors in [47] studied on secure hybrid VLC-RF Systems with Light EH. It shows that the radius of circle formed by illumination from a light source has positive effect on the secrecy outage performance and the height of LED light has a negative effect on the secrecy outage performance in indoor scenarios. In [48] authors discussed on dual-hop VLC/RF Transmission System with EH Relay under delay constraint. This enhances the coverage of VLC link by introducing a relay between the two hops. The relay is equipped with EH device to harvest indoor light energy and convert to electrical energy. The authors of [49] uses relay in providing low complexity and energy efficient solution through power transfer, and also extend overage of VLC systems. In [50] authors presented Energy-Autonomous Wake-up receiver using VLC. It uses solar cells as both VLC communication receiver and energy harvester. From all these references, it is found that the exact potential of EH in VLC alone is not exploited properly yet. The prospect of LED lighting systems known for low energy consumption is yet to be exploited for its energy availability in VLC. Therefore, this paper intents to inform emerging trends in wireless communication from RF to VLC. To further cement the appropriateness of energy efficient lighting source LEDs' capacity to provide sufficient energy for participating devices in network is investigated through case study. The case study is presented to confirm the energy available in LED lighting systems for harvesting.

C. Case Study: Sustainable energy for IoT devices in smart room through Visible Light Energy Harvesting

The case study considers a smart classroom to explain the VLC and prospect of light as alternative source of energy to meet the power requirement in wireless network. Consider a smart room well illuminated with most energy efficient lighting luminaries like LEDs in Fig. 5. IoT device e.g. Laptop in figure is the receiver deployed in VLC enabled network to access the internet. Streams of high speed data in '1's and '0's are transmitted through the photons of light imperceptible to user. Maintaining the proper line of sight(LoS), users are able to access high speed internet facility when Laptop is placed on a surface covered by incident light illumination. However, the stored energy in device is discharged over a time period simultaneously, hence it has to be plucked to a separate power supply to recharge its battery. On the other hand LEDs' light has large energy potential to supplement the power requirement of participating IoT devices.

The potential of electrical lighting as the alternative source of energy for wireless devices in the network is achieved in smart room. The energy contained in VL incident on laptop is harvested to meet its power requirement with energy harvester enabled in it. The SWIPT technology can be adopted to achieve the efficient usage of light sources. The integration of light EH in VLC enhances the optimization of VL usage. This technology can be built on the existing lighting infrastructure and be easily integrated in smart homes, smart cities where large energy efficient lighting systems are deployed. This extends the VL application in achieving three major milestones

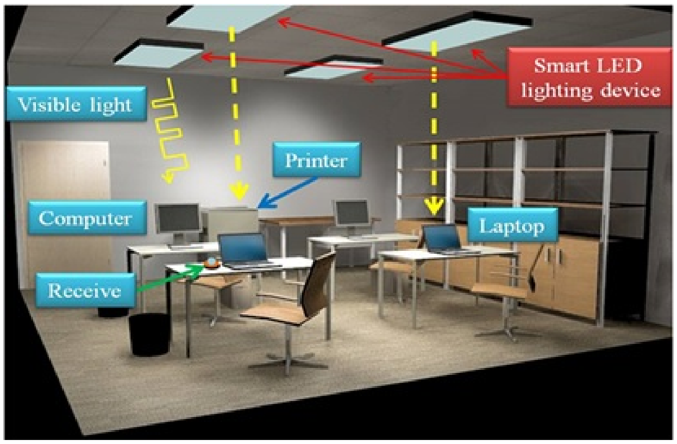

Fig. 5. Li-Fi Enabled Smart Room

i.e. source of illumination, medium for high speed data transmission and meeting the power requirement of IoT devices in the network. This technology can be extended to existing street lighting systems in turn curving down the surge in investment on installation of base stations for wider network coverage, adversely affecting the green communication initiative of 5G.

III. Challenges and Future Recommendation

In the earlier sections, we have covered all aspects of challenges of RF communication. The potential of VLC taking the future wireless communication to greater heights are also examined through understanding the VLC and light EH. The optimization of visible spectrum through innovation in VLC and its integration with RF offers new paradigm in fulfilling the green communication objective emphasized in 5G. The following research directions are presented with the prospect of taking the revolution in data communication by harvesting the VL spectrum potential.

A. Smart City: Energy Harvesting enabled VLC

Exponential deployment of base stations to meet the high speed data for billions of IoT devices does not stand an effective solution anymore. Health hazards, environment degradation, unusually high power consumption by large number of base stations in addition to spectrum crunch in RF Wireless communication possess the challenge to meet the expectation of 5G. However, VLs are in abundance around us but realization of its full potential is trending now only. The prospect of VL in transmission of streams of data has inspired the paradigm shift in exploiting the VLC as alternative to RF wireless communication lately. VLC is not a theoretical concept anymore yet harnessing its full potential is far from over. Further, VLs are known for its energy contain with the possibility of substituting the power requirement in wireless devices in the network [44]. Therefore this area, the exploitation of VLs for VLC remains an emerging trend of research interest. The prospect of integrating this technology on the existing infrastructure is even more appealing particularly for developing countries e.g. Bhutan where cost for infrastructure building is expected to dramatically reduce. Hence the future research may explore in replacing the existing lighting infrastructure with suitable luminaries, e.g. LEDs in home lighting, office and street lights which will be convenient to integrate for VLC in smart city.

B. Merging the VLC and 5G Technologies

The prospect of VLC encourages the optimal usage of VLs available around everywhere. So far VLC is concentrated mostly in realizing two major purposes: illumination and high speed data transmission resulted to deployment of LiFi [51]. 5G is for achieving data speed in gigabits inspired by energy efficient green technologies and powered by sustainable energy sources. Research works in harnessing the energy contain of light sources is a growing trend with very few works [48], [49] done in VL-EH. The abundance of VLs offers viable choice for its green, natural and as alternative sustainable energy sources. This has the potential of VLC integrated with EH towards achieving the objective of 5G wireless communication. Therefore, thorough investigation of energy contains in VLs and its integration to power wireless devices warrants in depth future research.

C. Bandwidth Enhancement

The relentless demand for high speed data with the emergence of 3G and 4G with billions of IoT devices deployed in the network puts tremendous pressure on already exhausting RF spectrum. The demand for spectrum usage has exponentially exploded while RF spectrum is expected to exhaust by 2020. This challenge which would lead to breakdown of world internet at any time soon has been instrumental in driving the paradigm shift in exploring unregulated free VL spectrum. The integration of VLC and RF with network handover technology is expected to dramatically ease the pressure on RF spectrum bandwidth. VL spectrum offering 10,000 times high bandwidth compared to RF has attracted more attention towards utilization of this 100x of THz bandwidth. Exploiting this huge bandwidth potential is a perfect platform for researchers to derive a best possible schemes/framework to use visible spectrum effectively. This integration also offers an opportunity to widen the network in RF deprived zones.

D. EH in VLC for IoT

Millions of new communication devices were added to the communication networks in 2015 [52]. The current emerging trend of IoT or Internet of Everything (IoE) deployed for different scenarios is further aggravating on unusually high power consumption by these devices. The unpredictability of battery lifetime of these devices also effects the standard QoS in data communication [53]. With exponential growth of IoT devices in the network, simultaneously power consumption by these devices are expected to surge the power requirement for communication alone. The varying intensity of VLs is known for its energy potential [46] at the same time fulfilling the mandate of illumination and data communication in VLC [44] [50]. The EH technique is the centre of attraction for its added value particularly for wireless communication. Meanwhile, except for the potential of EH in visible light, very little scientific research is carried out, that too mostly integrating with RF-EH [48] [49] thus far. Exploitation of VLs for EH presents an appealing opportunity where future researchers could work on integrating SWIPT technology in VLC for IoT cooperative network.

E. Security and Interference in VLC

The vulnerability of RF wireless communication has given way to this new paradigm shift in VLC. VLC otherwise optical wireless communication (OWC) has emerged as potential candidate to further the demand for high speed data where RF spectrum is suffocated for its shortage of available bandwidth. The VL cannot penetrate opaque objects while varying intensity imperceptible to human eyes offers two significant opportunity of enhanced data rates and immunity to security breakdown [54]. The prospect of availing high speed data within the illumination covered surface confined to specific zone makes the VLC, e.g. LiFi network free from interference which otherwise is the major threat in WiFi [55]. But this issue of security and interference in VLC still remains to be investigated because the conclusions drawn thus far have been based on the characteristics of light. Therefore, the further validation of these issues presents lucrative space for future research works because interference management in VLC still remains to be investigated thoroughly [56].

F. VLC in vehicular adhoc networks

The rapid advancement in vehicular technology is another factor demanding the communication technology to evolve even faster. It has become vital to enable vehicles communicate ultimately linking adjacent cities to a smart cities. The vehicular ad-hoc networks (VANETs) provides the most imminent communication technologies with the prospects in data disseminating about traffic congestion, traffic accidents, and many other social issues [57]. The prospect of VLC in vehicular communication also looks promising with RF spectrum running out. The enhanced connectivity among vehicles would become reality for new applications ranging from safety to traffic management, information sharing, infotainment [58]. The application of VLC in this area has tremendous opportunities to expand the effective utilization of vehicular lights. This field is a growing research field with plenty of scope for scientific investigation.

G. VLC for Healthcare Applications

The full deployment of IoT technology will have tremendous positive impact across all spectrum of applications. Its applications in various healthcare monitoring systems would be even more exciting. However its deployment requires installation of lot of power efficient wireless terminals [59]. Applications of biomedical technology in healthcare systems are also known for power inefficiency. The wireless energy transfer in such applications through EH are explored such as transfer of energy through living body [60] [20]. Despite integration of IoT technologies in healthcare systems, health concerns due to EM radiation in RF and microwave remains intact limiting its usage in areas such as hospitals, industries and business [61]. Very little is done in visible spectrum usage in healthcare applications which otherwise have huge prospect particularly in information dissemination through VLC technology [61]. Possibility for ease of deployment on existing infrastructure and hazardless visible spectrum makes it more appealing for applications in RF restricted areas.

H. Framework for EH using Visible Light

Each of IoT devices need to be powered in order to ensure the effective participation in the network. Power consumption of each device amounts to large energy requirement to sustain the network connectivity, ultimately rising the concern on power sustainability. VLs abundantly available from electrical lighting systems are known for its huge energy potential [44]. With this knowing, EH in VLC has started gaining significant interest of researchers in a way to generate the green natural and sustainable energy sources for communication devices under different scenarios [62] [58]. Few further prospects of EH in VLC are examined [63]. Yet these works still remains imaginary where future researchers can work on the development of proper framework for EH in VLC.

IV. Conclusion

VLC is an emerging research field prompted by challenges faced in RF communication for its limited spectrum and health concerns. The drive for energy efficient and cost effective lighting systems by deploying LEDs makes this technology attractive platform for researcher to take wireless communication to newer height. The potential of visible spectrum is examined on the basis of available unlicensed free bandwidth in EM spectrum. The prospect of data transmission through the concept of VLC technology is analyzed where LiFi deployment has motivated its exploitation towards interference-less high speed data. To further claim the significance of VLC, comparative study on RF and VLC is stated in this paper. In order to supplement the green communication and sustainable energy source initiatives for wireless communication, the prospect of EH from lighting systems is examined. A case study is presented here on the basis of lighting luminaries known for its huge energy source potential. The case study is aimed to project the integration of EH in VLC to optimize the visible spectrum utility in achieving three major milestones: illumination, data communication and sustainable energy source for participating IoT devices in the network. The possible future research works in VLC and EH-VLC is presented through recommendations inspired by drawbacks of RF and RF-EH technologies. This paper suggests the significance of integrating VLC and RF communication technologies in the era of IoT/IoE to achieve the objectives of 5G networks and green communications.

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