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Electric-Field Energy Harvesting From Lighting Elements for Battery-Less Internet of Things

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ABSTRACT Internet of Things (IoT) is envisioned to bring the Internet connection to every object/service/process to seamlessly and efficiently observe, manage, and control pervasive systems. This necessitates the employment of wireless standalone devices in excessive numbers. However, periodic maintenance of thousands, maybe millions of batteries will add massive workload and replenishment costs to the operation. In order to alleviate this problem, we introduce a totally new energy harvesting paradigm based on utilizing ambient electric-field in the vicinity of lighting elements. A low voltage prototype is designed, constituted, and evaluated on a generic 4 × 18W-T8 ceiling-type fluorescent troffer. Empirical results disclose the availability of 1.5 J of energy that can be gathered in 30 min when a copper plate, i.e., the harvester, covered by a reflective dielectric is employed. The design issues to achieve the best performance attainable are addressed in both theoretical and experimental manners. The physical model of the proposed technique and an applicable circuit diagram for its execution are provided. We also point out possible application areas, and protocol stack requirements specific to our proposal to conveniently enable self-configuring IoT services, which are free from battery constraints.

INDEX TERMS Electric field, energy harvesting, wireless networks, IoT, lighting elements, fluorescent troffer.

I. INTRODUCTION

Internet of Things (IoT) is a prominent enabling technology that seamlessly interconnects everyday objects to grant a whole new set of benefits including numerous types of services [1]–[3]. The unification of state-of-the-art technologies has accelerated the extensive growth of IoT paradigm. However, the ever-increasing number of Internet-enabled devices brings along its own challenges. Even though the majority of IoT devices have duty cycling, their operation remarkably suffers from limited energy capabilities. This issue necessitates the employment of an auxiliary and/or a totally distinct power source [4]. Hence, exploiting light, heat, motion, and electromagnetic (EM) radiation comes into prominence to mitigate the ongoing energy constraints of IoT devices.

The self-sufficient and maintenance-free operation of IoT paradigm can be sustained by exploiting a stray source or converting energy from one form to another. This phenomenon, i.e., energy harvesting (EH), is able to prolong the lifetime of wireless devices dramatically [5]. However, provision of perpetual and sufficient power is mostly ambiguous due to highly random and unpredictable nature of harvestable sources. This issue brought research efforts to focus on finding more reliable and efficient energy harvesting techniques. By this means, E-field EH stands as a perfect candidate by operating regardless of ambient parameters, providing adequate power density; low complexity; and excellent energy continuity [10].

Preliminary studies of E-field energy harvesting are first performed on power grid assets due to high-voltage resultant E-field in abundance. Attractive outcomes of this method in providing advanced monitoring and intelligent control accordingly directed research efforts to develop low-voltage models. In this regard, lighting elements, i.e., the integral part of daily human life, come to the forefront due to strong and continuous E-field gradient in the vicinity [6]. This raises interesting design questions to be addressed for the battery-less execution of IoT services. The Internet-capable and E-field powered pervasive nodes actively probe the environment to collect information about parameters of interest, process the acquired data, and notify an upper level authority for further decision making procedures. By this means,

the extension of web paradigm to monitoring, control and management of the everyday life objects can be efficiently maintained [2].

Even though there are several approaches to adopt E-field EH in wireless networking, there is currently no effort intended explicitly to power IoT services by utilizing illumination assets. Regarding this, and the aforementioned issues, we develop a totally new energy harvesting model that provides;

- ease of implementation, flexibility and interruption free operation: On the contrary of related existing approaches, our proposal is based on embedding harvesters into E-field emitting lighting elements to acquire energy without effecting their operation. To do that, we constituted mathematical model of the harvester system and evaluated it in both theoretical and experimental manners. As a result, application specific design principles are emphasized to maximize the energy to be harvested, and also to allow harvesters and sensors to be utilized in a more convenient and practical way, i.e., deploy and forget fashion.
- less complex, and more efficient circuitry: As the energy that can be acquired by harvesting efforts is quite limited in average we tried to eliminate some energy depleting but non-mandatory, i.e., optional, components to benefit more from the source being utilized. We carried out several experiments with various energy storages to profile the available energy. By trading on charging time vs. accumulated energy the optimal storage, which saturates around the voltage that sensors operate, selected to make use of any buck and/or boost type converter unnecessary. The need for energy buffers, auxiliary batteries, filters and additional safety procedures are also eliminated.
- increased luminaire efficiency: As copper plate, i.e., energy harvester, to be employed has lower reflectance than matt-white plane floor of fixture chest, i.e, the integral part of energy source, we mounted the plate with a non-electrical and a more reflective thin film white paper to, at least, not affect the lighting process. Experimental results disclosed an increment in illuminance by %5.2 after this alteration.
- highly enhanced harvesting performance: We propose an E-field energy harvesting mechanism that is able to provide roughly 1.5J of energy in every 30min.

with minimal installation, design, and maintenance costs. The theoretical inspections and experimental findings have predicted that the proposed method of E-field energy harvesting seems quite promising to extend the lifetime of wireless systems. Thereby, our approach stands as a key enabler for the pervasive deployment of self-operable and self-configuring IoT devices.

The remainder of this paper is organized as follows. First we commence with a literature review of existing energy harvesting techniques. Then we extend our study to the theory of E-field EH, and the related existing efforts on the area. In Section III, we address fundamental design principles that need to be followed, and accordingly propose a totally new harvesting technique to be utilized with lighting elements. This is followed by the performance analysis and a detailed discussion of our proposal. While Section VI discloses the possible applications that can be powered by the proposed model, Section VII points out the protocol stack requirements for battery-less IoT services. Finally, this paper is concluded.

II. EXISTING ENERGY HARVESTING TECHNIQUES

Exploitable energy sources can be broadly divided into four groups as light, heat, motion, and electromagnetic (EM) radiation [5], in which availability, controllability, and predictability of these sources determine the models and the specifications of the harvesting procedures that are going to be employed [7]–[9]. By regarding this separation, the frequency of preference, and the motivation of our proposal some leading energy harvesting techniques are discussed below, and a more illustrative comparison is depicted in Table 1.

A. LIGHT

Power provision from light propagation means converting visible lights, emitted from either sun or artificial sources, into usable electric power [8]. Due to a chemical phenomenon, namely photo-voltaic (PV) effect, PV cells emit electrons when they exposed to light which yields in generating electrical energy [9]. In outdoor, sunlight power is converted by multiple PV embedded solar panels [5]. However, their operation strictly depends on time varying uncontrollable parameters such as weather and season. This issue results in limited applicability in continuous operation requiring mission critical applications [11]. In indoor, more specialized photo-voltaics, which are better suited for diffused lights, are utilized for taking advantage of the rays that are being emitted from artificial light sources [10].

B. MOTION - VIBRATION

Kinetic energy harvesting (KEH) focuses on mechanical stress and/or movement resultant motion variations and vibrations to acquire usable electrical power. The well-studied type of this method, i.e., airflow EH, is based on converting wind power by using AC generators to enable wide-scale communications in open areas. Besides, more specialized materials, i.e., piezoelectrics, are being utilized for attaining energy from highly random and mostly unpredictable kinetic sources in both indoor and outdoor domains [5], [8]. Although the airflow-based systems offer sufficient power conversion efficiencies, their operation is highly threatened by the environmental parameters similar to sunlight-driven procedures. Piezoelectric materials, in comparison, operate regardless of the ambient variables; however, fabricating a generalized harvesting system, for especially vibrating sources, is a challenging issue due to source specific design requirements [8], [10].

TABLE 1. Comparison of existing energy harvesting techniques.

	Type	Characteristics	Method	Power Density	Advantages	Disadvantages	Applications	Literature
Light	***Solar***	Uncontrollable, Predictable	PV Panel	$15-100$ mW/cm^2	Environmental, Independent of grid, High output voltage	Not always available, Sensitive structure, Deployment constraints	Wireless sensors, Cellular base stations	[5], [7], [8], [9]
	Artificial	Partly-controllable, Predictable	PV Cell	$10-100$ $\mu W/cm^2$	Abundant in indoor, Easy to implement	Low power density, Sensitive structure	Wireless sensors, Portable devices	[5], [9] [11], [12]
Temperature gradient	-	Uncontrollable, Unpredictable	Peltier, Thermocouple	$\simeq 50$ $\mu W/cm^2$	Environmental, Low maintenance, Scalable	Not always available, Requires eff. heat sinking Low power density	On-body sensors, Wearables and consumer elec.	[5], [8], [9], [17]
Motion	***Airflow***	Uncontrollable, Unpredictable	Piezo Turbine, Anemometers	100 mW/cm^2	Environmental, Independent of grid, Available day and night	Big in size, Hard to implement, Requires construction	Wireless sensors, Cellular base stations	[7], [14] [17]
	Human-based	Controllable, Partly-predictable	Piezoelectrics	200 $\mu W/cm^3$	No ext. power source, Compact configuration, Light in weight	Charge leakage, Brittle materials, Highly variable output	On-body sensors, Wearable devices	[5], [8], [9], [10]
EM Waves	-	Partly-controllable, Partly-predictable	Rectenna	$1-10$ $\mu W/cm^2$	Abundant in urban lands, Allows mobility	Scarce in rural areas, Low power density, Distance dependent	Wireless sensors, RFID	[5], [7], [8], [12]
EM Fields	***M-field***	Controllable, Predictable	Current transformers	150 $\mu W/cm^3$	No ext. power source, Easy to implement, Non-complex structure	Requires high and perpetual current flow, Safety vulnerabilities	Wireless sensors, Monitoring systems, Remote reading	[12], [14], [15], [17]
	E-field	Controllable, Predictable	Metallic plates	N.A.	No need of current flow, Easy to implement, Always available	Being capacitive, Mechanical constraints	Wireless sensors, Online surveillance	[10]–[26]

C. HEAT

Heat energy can be scavenged by benefiting from two distinct abilities of materials, i.e., thermo-electricity and pyro-electricity [9]. Thermo-electricity, the most utilized, is based on a physical phenomenon, namely Seeback Effect, in which a junction constituted by two conductors expands in a certain direction due to a thermal difference. The attained energy can be easily adjusted by altering the connection of pairs as series and/or parallel. Although harnessing power from temperature gradients sounds promising due to its ubiquitous characteristic, there is a fundamental limit, namely Carnot cycle, to the maximum efficiency of power extraction [8]. Due to their miniature size, thermo-generators are widely used in low-power time-uncritical consumer electronics solutions [10].

D. ELECTROMAGNETIC WAVES

With the unprecedented growth in the number of wireless devices, Radio Frequency (RF) EH has received significant attention in recent years [7], [8]. Due to the broadcasting nature of wireless communication, easily attainable and efficiently utilizable EM waves ease the realization of battery-less IoT networks. In urban areas, the ever-growing RF systems are about to unseat the conventional EH methods that are destined to run remote services of Smart Cities. For indoor, EM signals emitted from modems, routers, smartphones, and laptops are collected, and accordingly converted by specialized power rectifying antennae to operate minuscule of power requiring Smart Home/Building actuators. RF EH provides sufficient solutions in exploiting under-utilized EM waves; however, its utilization is not recommended in mission-critical applications due to unpredictable, distortive, and inflexible characteristics.

E. ELECTROMAGNETIC FIELDS

In addition to aforementioned sources, wireless autonomous devices can be also powered by profiting from electromagnetic fields. Magnetic field (M-field) energy harvesting, in particular, is based on coupling the outward field flow of AC current carrying conductors by clamping the field source with a current transformer [7], [10], [12]. This method is able to provide sufficient power as long as there exist adequate current flow on the conductor of interest. Being bulky and necessitating additional safety procedures, due to the physical contact with high-voltage terminal, restrict its employment in certain applications. However, for online condition monitoring of grid assets, it outperforms many techniques, i.e, sunlight and airflow EH, with its eligible features.

E-field EH, in similar, exploits the free electric charges induced on a conductive material due to a voltage gradient. On the contrary of existing scavenging procedures, which require specialized harvester fabrication, E-field energy harvesting is simply actualized by utilizing any conductive material available. The field that is being emitted is obstructed by the conductor which results in a displacement current to be drained for energy provision. E-field is the only source that is neither intermittent nor dependent on the load [13]. As the voltage and the frequency are firmly regulated and exactingly maintained, the E-field is therefore stable and predictable in its behavior [15]. It provides an adequate rate of power, and has the characteristics of low complexity and excellent energy continuity. Thus, it can be referred as the most promising way to compose long-term and self-sustainable communication systems notwithstanding the ambient factors [14].

III. ELECTRIC FIELD ENERGY HARVESTING - *A REVIEW*

According to fundamentals of electrostatics, electric charges distributed in a closed surface result in a radial E-field. This time-varying field produces an AC current I_d, i.e., displacement current, which is stated as Maxwell's following equation

$$I_d = \epsilon \int_s \frac{dE}{dt} \cdot ds \tag{1}$$

where ϵ is the absolute permittivity, and E is the electric field intensity. An apposed conductor helps I_d to drain the electric charges, and accordingly charge a storing element, C_s. The energy accumulated in this storage is expressed as

$$E = \frac{1}{2} C_s V^2 \tag{2}$$

where C_s is the capacitance and V is the voltage collected. As this energy is gathered by exploiting the free charges-induced E-field, this method can be named as Electric-field Energy Harvesting (EFEH) [10]–[26].

Preliminary work on this emerging topic is first experimented on middle/high voltage (MV/HV) overhead transmission lines, utility assets and substations due to the abundance of E-field formed by excessive levels of voltage. As a result of high tension, sharp edges and corners needed to be rounded for avoiding air ionization-based partial discharges, which yielded in tube and/or donut-shaped harvester designs. The proposed harvesting model operates as a generic current source to run the attached devices that monitor, predict and identify causes of failures, i.e., sagging, icing, and vibration, to maintain more reliable, high-efficient and less-interrupted operation. The empirical results disclosed the competence of EFEH in powering the wireless devices for acceptable intervals.

The concept of EFEH, and the corresponding tubular harvester, is first disclosed by [12], in which theoretical and empirical studies carried out to investigate the validity of the proposed method. This discussion is further detailed in [14], where a transformer-added harvesting structure is experimentally evaluated. In [15], instead of utilizing a tube-shaped harvester, a new model based on circular metallic plates is presented. Following these, the authors in [16] design a multi-layer cylindrical harvester to satisfy the varying power needs of the specialized network elements. In a similar study, energy availability of the cylindrical harvester is investigated with respect to capacitance variation [17]. As opposed to above-mentioned approaches in the area, two distinct proposals, [18], [19], represent a rectangular design for ease-of-utilization, and an insulator-embedded structure for enhanced security, respectively. The most recent works on HV [20]–[22] are further justify the EFEH concept in building wireless sensor networks (WSNs) [27] which are free from battery constraints.

The successful trials on MV/HV eventually motivated researchers to implement the existing methods of EFEH on low-voltage (LV) systems. Although [19] declares that the EFEH concept might not be a feasible option for LV, this claim is invalidated by the forward research efforts [23], [24], [25]. In [23], 47 μW of power is extracted with 60 cm of aluminum (Al) foil stuck on a 220V AC power line. This work is taken a step further with [24], which is mainly focused on enhancing the switching performance. Although the harvester length is reduced to one third, from 60 to 20 cm, about 20 mJ of energy is scavenged in 15 min with this approach. Similar method is re-handled in [25], where a 60 cm long harvester, specialized for two-wire power cords, is able to extract 1.4 μW of power from a 100V AC supply. Another work on low voltage is presented by [10], where a multi-layer harvester destined to run more power requiring network components is proposed. This approach collects 12.5 mJ of energy in 15 min. As an alternative, Linear Technology has brought a new perspective to the area with their in-plane plates model [6]. It includes copper (Cu) plate placement under fluorescent fixtures to exploit the ambient field flow. This model is claimed to provide roughly 200μW of utilizable power; however, the setup is bulk, hard to employ, and adversely affects light propagation. A more illustrative comparison of above-mentioned approaches is depicted in Table 2.

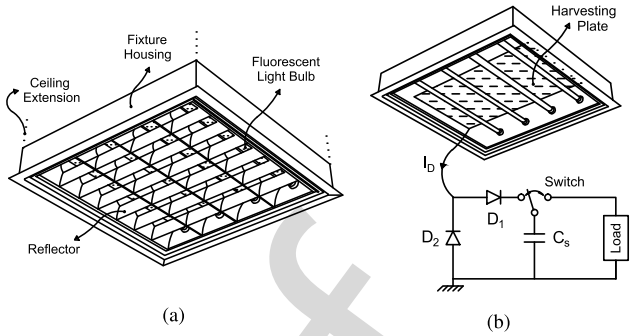

FIGURE 1. (a) Conventional overhead 4-light fluorescent troffer model; (b) Harvester utilization and test circuit for the proposed E-field energy harvesting concept (patent pending design [28]).

Although there are plenty of studies on both high and low voltage, none of them broadly discloses the requirements of networks to be powered by this newly-emerging harvesting paradigm. This work therefore addresses the challenges on network domain, investigates the applicable communication architectures and outlines the possible application scenarios as well as mechanical structure and circuit design considerations. The idea presented in [6], and our preliminary work on this topic [26] are taken as the basis of this paper to build a more flexible and efficient EFEH system for IoT-enabled wireless networks.

IV. DESIGN OF AN E-FIELD ENERGY HARVESTER

As one of the main concerns of wireless sensor nodes is providing as much energy as possible at the smallest cost; volume; weight; and recharge time [27], an optimal harvester design is highly recommended for the best performance

TABLE 2. Comparison of existing E-field energy harvesting approaches.

	Literature	How the results gathered	Harvester type	Power Output	Energy Storage	Comm. Method	Voltage Output	Harvested Power/ Energy	Reporting Frequency	Application
Low Voltage	[6]	Experimentally	Two (in plane) Cu Plates	Continuous	No	N.A.	3.2V	200μW	N.A.	Battery-less devices
	[10]	Experimentally	Double-layered Cylindrical Al/Cu Sheets	Intermittent	Capacitor (2.2μF)	Internet -based	3V	12mJ	15min.	WSNs for Smart Grid (SG)
	[23]	Experimentally	Cylindrical Al Foil	Intermittent	Capacitor (47μF)	RF -based	10.9V	47μW	42sec.	WSNs for SG
	[24]	Experimentally	Cylindrical Cu Sheet	Intermittent	Capacitor (100μF)	ZigBee	3.3V	20mJ	300sec.	Home automation, Smart Grid
	[25]	Experimentally	Semi tubular Two Cu Sheets	Intermittent	Capacitor (100μF)	ZigBee	4V	1.4μW	250sec.	Building energy management
	[26]	Theo./Exp./Sim.	Cu Plate	Intermittent	Super-capacitor (0.1F)	Internet -based	5V	1.25J	N.A.	IoT networks
Middle Voltage	[18]	Theo./Sim.	Cylindrical Al Electrode	Continuous	No	N.A.	N.A.	100mW	N.A.	Smart Grid monitoring networks
	[19]	Theo./Exp./Sim.	Al box	Continuous	Capacitor (330μF)	ZigBee	3V	17mW	N.A.	SG sensors for MV/HV assets
	[20]	Theoretically	Cylindrical Al Electrode	Continuous	No	N.A.	13V	17mW	N.A.	Power-line monitoring for SG
	[22]	Theo./Exp./Sim.	Two Cylindrical Electrodes	Intermittent	Super-capacitor (0.47F)	RF -based	3.26V	110mW	90min.	Battery-less monitoring of SG assets
High Voltage	[12]	Theo./Sim.	Two Plates (Parallel)	Continuous	No	N.A.	N.A.	95mW	N.A.	WSNs in power systems
	[14]	Exp./Sim.	Cylindrical Electrode	Continuous	No	RF -based	9V	370mW	N.A.	Online condition monitoring of HV power lines
	[15]	Theo./Exp./Sim.	Two Circular Plates (Parallel)	Intermittent	No	N.A.	N.A.	10.6mJ	1min.	Wireless condition monitoring sensors
	[16]	Theoretically	Cylindrical Electrode	Intermittent	Capacitor (0.1μF)	N.A.	N.A.	N.A.	N.A.	Power-line monitoring networks
	[17]	Theo./Exp./Sim.	Cylindrical Electrode	Intermittent	Super-capacitors (3.6F)	N.A.	5.5V	16.4mW	20min.	Power-line monitoring networks
	[21]	Experimentally	Plate	Continuous	No	N.A.	N.A.	645mW	N.A.	Online condition monitoring

attainable. Now, consider a system of one conductive plate, specifically copper, closely placed under an overhead fluorescent troffer in parallel, as roughly depicted in Fig. 1. The copper plate placed obstructs the time varying flow of E-field around the fluorescent tubes, where the field induced electric charges are transferred by a displacement current I_d. As this plate capacitively divides the ground-to-fixture potential, I_d accordingly charges the capacitors formed by the copper plate. In other words, splitting up the field by conductors not only results in a voltage difference, but also forms parasitic in-plane capacitances which are energized by capacitive coupling. A more illustrative representation of the above-mentioned scenario and distribution of the formed stray capacitances are depicted in Fig. 2(a), (b).

With respect to our measurements and the fundamentals of electrostatics, fluorescent tubes are assumed as uniform sources of E-field to simplify the model given by Fig. 2(b), and therefore reduce the computational complexity of theoretical consideration. As seen in Fig. 2(c), the plate placed between the ceiling and fluorescent tubes acts as a voltage divider, and in this circumstance the major contributions are only due to one C_f and a serially connected C_h. It should be noted that the fringing capacities, and also the other fringing resultant factors are neglected in the following theoretical investigation.

The equivalent impedance of the simplified model Z in Fig. 2(c), and the voltage u on the load Z_L are obtained as

$$Z = \frac{Z_L}{1 + jwC_hZ_L} + \frac{1}{jwC_f} \quad [\Omega] \tag{3}$$

$$u = u_0\left(\frac{jwC_fZ_L}{1 + jwZ_L(C_f + C_h)}\right) \quad [\mathrm{V}] \tag{4}$$

where u_0 and w represent phase-to-ground rms voltage and angular frequency of the power-line, respectively.

The capacitance from bulb to harvester, i.e., C_f, can be stated as

$$C_f = \frac{2\pi\epsilon l}{\cosh^{-1}(d/r)} \quad [\mathrm{F}] \tag{5}$$

where l is the tube length, r is the tube radius, and d refers to vertical distance from tube to plate. Similarly, the capacitance from harvester to ground, i.e., C_h, can be given as

$$C_h = \frac{2\pi\epsilon l}{\ln(2H/r)} \quad [\mathrm{F}] \tag{6}$$

where H denotes the distance from tube's center to ground. Note that, ϵ means absolute permittivity, i.e, $\epsilon = \epsilon_0\epsilon_r$, where ϵ_0 and ϵ_r refer to vacuum and relative permittivities, respectively. As tube-to-ground distance is quite small in our approach, the resting capacity is calculated by considering the voltage difference between the harvester and ground planes.

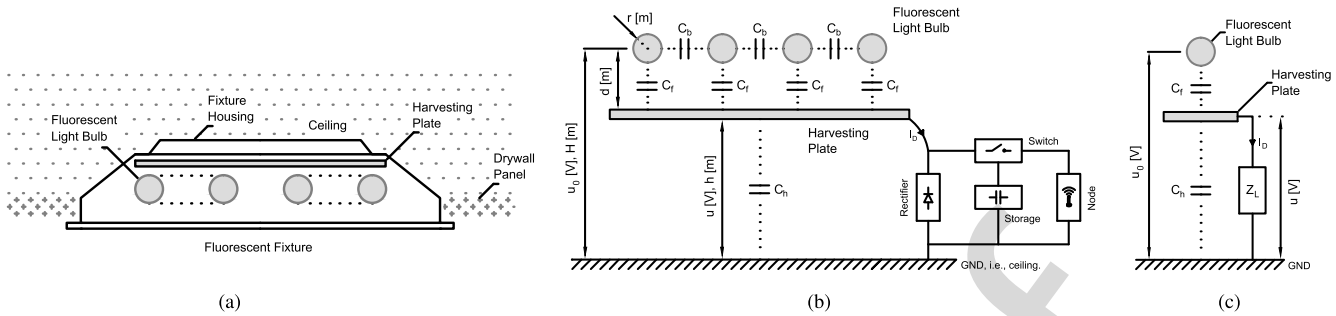

FIGURE 2. **(a) Cross section depiction of 4-light fluorescent troffer with harvesting plate placement; (b) Physical model of the proposed EFEH concept; (c) Simplified model of the proposed EFEH concept.**

The voltage u on the load Z_L are re-expressed in (14), as shown at the bottom of this page, by inserting (5) and (6) into (4). By substituting constant values in (14) with

$$\begin{cases} m = \ln(2H/r)2\pi\epsilon l & (7) \\ k = \ln(2H/r)\cosh^{-1}(d/r) & (8) \\ a = 2\pi\epsilon l(H-d)\cosh^{-1}(d/r) & (9) \end{cases}$$

the load voltage u can be therefore simplified as

$$u = u_0\left(\frac{jwZ_L m}{k + jwZ_L(a+m)}\right) \quad [\mathrm{V}] \tag{10}$$

If Z_L is assumed as an ohmic load, the obtainable power from the harvester can be calculated as

$$P = \frac{|u|^2}{Z_L} \quad [\mathrm{W}] \tag{11}$$

When $\partial P/\partial Z_L = 0$, the optimal load impedance $Z_{L_{opt}}$ can be found by

$$Z_{L_{opt}} = \frac{k}{w\cdot(a+m)} \quad [\Omega] \tag{12}$$

where the maximum achievable power is therefore calculated by substituting Z_L by (12) in (11), i.e., $P_{max} = P(Z_{L_{opt}})$, as

$$P_{max} = P(Z_{L_{opt}}) = \frac{Z_{L_{opt}}(wmu_0)^2}{k^2 + (w(a+m)Z_{L_{opt}})^2} \quad [\mathrm{W}] \tag{13}$$

From (13), also considering (7), (8) and (9), it can be said that the maximum achievable power P_{max} increases with the rms voltage of the power-line u_0, relative permittivity ϵ_r; and decreases with the distance from tubes to plate d; however, it has a convex behavior for load resistance R. Fig. 3 represents the variation in obtainable power P with respect to voltage u_0, load resistance R, relative permittivity ϵ_r, and distance d, respectively.

In addition to above-mentioned metrics, to extract more power from the surrounding field, the harvester must be perpendicular to the tubes, and the size of it must be as large as possible. To validate these, we performed complementary experiments. As seen in Fig. 4, the proposed model is tested for three different scenarios, i.e., varying angular aperture, plate area, and E-field intensity. In the first case, Fig. 4(b), the angular aperture between the harvester and fluorescent bulbs is increased from 0° to 30° and 60°, respectively. In the second case, Fig. 4(c), the plate area is altered by an increment of $\simeq$ 200cm^2. In the last scenario, Fig. 4(d), the number of light emitting fluorescent bulbs are changed to observe the alteration in obtainable power with respect to E-field intensity.

By regarding theoretical investigation, dimensional limits of the fluorescent fixture, and the corresponding results given in Fig. 4(e),(f),(g), the size, position and the structure of the E-field energy harvester can be determined to obtain the best performance achievable. These aspects can be also regarded as fundamental guidelines for the design of battery-less sensory structures and/or wireless services. In this sense, any AC-powered lighting element can be conveniently turned into a generic power source without any effect in its operation. This issue is expected to revolutionize the structure of today's battery-constrained communication architectures.

V. PERFORMANCE EVALUATION

In order to test the validity of our proposed model, a conventional $4\times$ 18W-T8 type $60\times60\times10$cm overhead fluorescent troffer is utilized. To prevent a galvanic contact with the fixture, providing ease of implementation, and to enable the best performance achievable the copper plate is adjusted as 50×50 cm in size, and placed 1cm away from the fluorescent bulbs as in Fig. 2(a) by regarding the design aspects disclosed in Section IV. The diagram seen in Fig. 1(b) refers to a test circuit utilized for the preliminary experiments, which is further improved as in Fig. 5(c) to constitute a more generalized harvesting system.

The main objective of the conceptual model given in Fig. 5(c) is to drain I_d and collect the charges in C_s, until

$$u = u_0\cdot\frac{jw2\pi\epsilon l\ln(2H/r)Z_L}{\ln(2H/r)\cosh^{-1}(d/r) + jwZ_L[2\pi\epsilon l\ln(2H/r) + 2\pi\epsilon l\cosh^{-1}(d/r)]} \quad [\mathrm{V}] \tag{14}$$

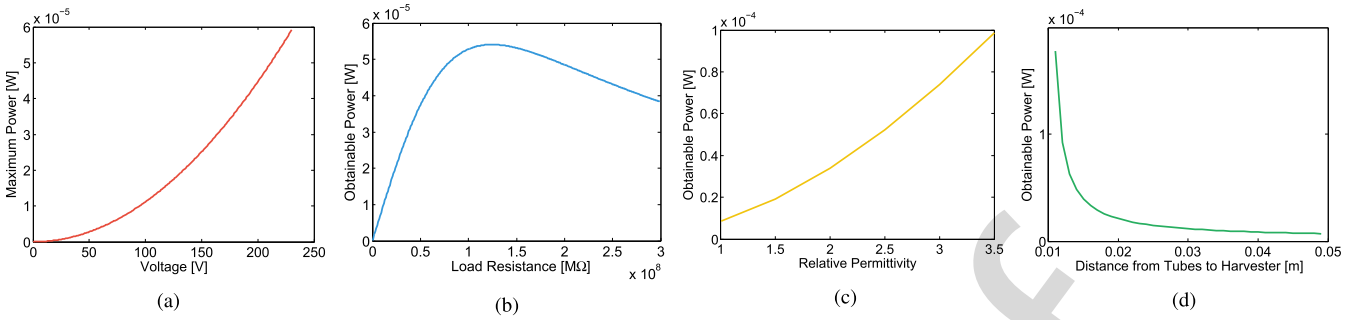

FIGURE 3. (a) Maximum available power P_{max} [W] vs. nominal voltage u_0 [V]; (b) obtainable power P [W] vs. load resistance R [MΩ]; (c) obtainable power P [W] vs. relative permittivity ϵ_r; (d) obtainable power P [W] vs. distance from tubes to harvester d [m].

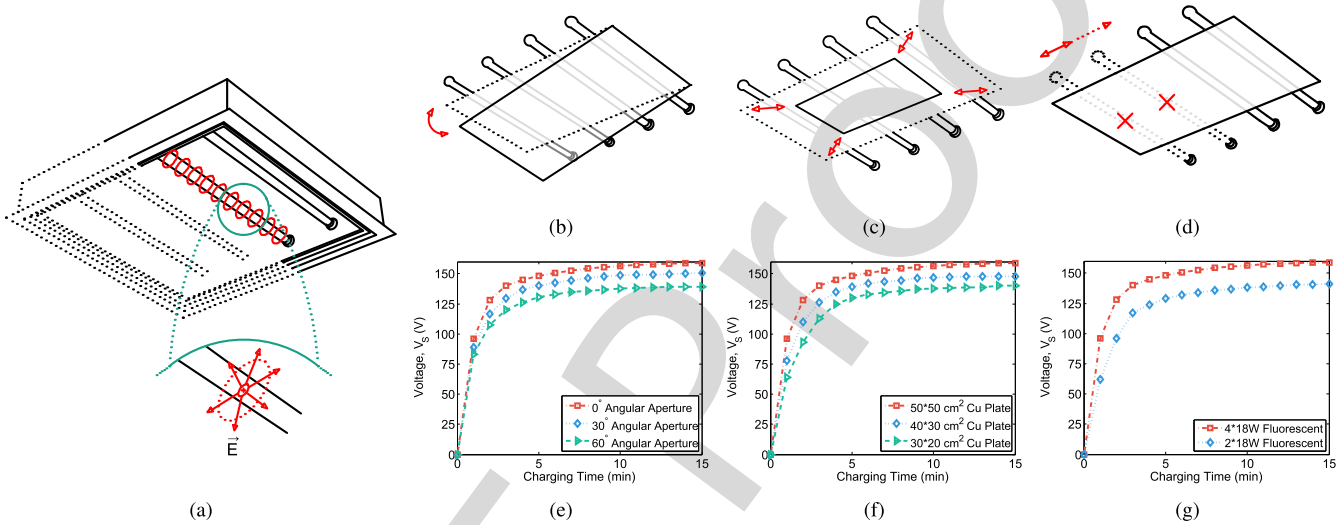

FIGURE 4. (a) Representative depiction of the E-field lines on a cylindrical source, i.e., fluorescent tube; (b) Testbed for angular aperture; (c) Testbed for plate area; (d) Testbed for field intensity, i.e., voltage source; (e) time vs. accumulated voltage for varying angles; (f) time vs. accumulated voltage for varying plate sizes; (g) time vs. accumulated voltage for varying number of fluorescent tubes.

the stored energy becomes sufficient for sensing; processing; and transmission. The copper plate obstructs the time-varying flow of E-field in the vicinity of the fluorescent fixture, which is followed by concentrating the acquired electric charges into C_{in} after being rectified. The rectifier is for both converting the alternating current, and preventing the scavenged energy from back feeding [4].

The block stated as ACC in Fig. 5(c), i.e., autonomous connection circuit, is for switching between harvesting and nodal operation stages [19], [29], [30]. This circuit simultaneously compares the voltage on input storage C_{in} and accordingly enables charge transfer to the primary storage C_s when the harvested energy is sufficient enough for nodal operation. Then it disengages C_s from the circuitry for turning back to harvesting period when the voltage drops below a certain threshold. This operation not only prevents the undesired discharge of C_s, but also allows more frequent transmissions as the time spent on harvesting stage is shortened. It should be noted that this process can be either performed by a low-power processor, a distinct one or the attached device's, or by a simple circuitry which offers a more robust solution. The given regulator block adjusts the output voltage of the harvester system for the wireless device to be attached. Both C_{in} and C_s can be selected as same-featured super-capacitors without loss of generality.

As the energy that can be gathered by harvesting techniques is mostly limited, utilization of low-loss rectifiers; power-saving processors; and more efficient regulators are highly recommended. In other words, from beginning to end each process requires the most efficient operation possible [4]. Since, any decrease in the amount of energy consumed on the harvester side directly affects the sensor lifetime, which will accordingly increase the communication reliability. It is also essential to enhance the energy storage capabilities to alleviate the rising demand for better lifespan. Thus, super-capacitor employment is highly recommended due to their more charge/discharge cycles; higher efficiency; and longer lifetime characteristics. In addition to each component being optimized for low power consumption, intelligent system/stage-level power-saving algorithms should be

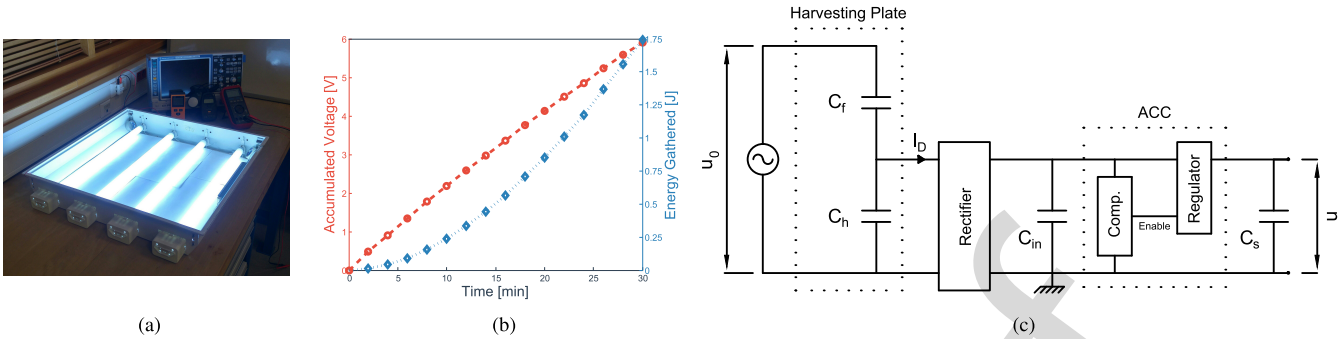

FIGURE 5. **(a) Measurement setup -with paper mounting; (b) time vs. accumulated voltage & energy on C_S; (c) Equivalent circuit diagram of the proposed EFEH concept.**

also developed and integrated into both hardware and software design of EFEH-powered IoT devices for enhanced longevity [31].

In order to estimate the energy profile of our harvester system, and accordingly determine the circuitry to be employed a series of experiments were performed. We tested a plethora of capacitors and analyzed their performance in terms of charging time versus accumulated energy. The preliminary results revealed that, it is possible to gather 1.5J of energy, on average, in 30min with our proposed harvesting model, i.e., 0.5J of energy in 15min, Fig. 5(b). In the light of this outcome, 0.11F of super-capacitor is selected for the storage as it saturates roughly at 5V which is the exact voltage required by a great majority of sensor nodes on the commercial domain [10]. Therefore, employing any converter-like component to further adjust the output voltage becomes unnecessary. As the ongoing circuit complexity constraints of conventional harvesters can be resolved, the rate of power transferred to the load can be also enhanced by this approach. As a result, 3.3V level is set as sub-limit for nodal operation, which determines duty cycle of the proposed EFEH system. The result, Fig. 5(b), points out to a remarkable improvement for the concept of energy harvesting when the existing power provision architectures are considered.

The proposed harvesting procedure enables ease of employment due to the neutral bus situated in the vicinity of the fluorescent fixture. In other words, there is no need for peeling of concrete surface and/or dealing with cabling to complete the harvesting circuitry on the contrary of existing efforts [23], [24]. This design also offers a more secure implementation due to necessitating no galvanic contact with the field emitting parts unlike magnetic field-based counterparts [12].

To ensure interruption-free operation, we further improved our model and performed additional experiments for its validation. As copper plate has a much lower reflectivity in contrast with the matt-white plane floor of the fixture chest, it is expected that copper placement may adversely affect the luminaire efficiency. To at least not decreasing it, we mount the plate with a non-electrical and a more reflective white paper as seen in Fig. 5(a). The measurements taken by a lux meter point out to an increase in illimunance by 5.2%, i.e., from 984 to 1035lx at a vertical distance of 60cm. As the theoretical consideration discloses, negligible increment in the absolute permittivity due to dielectric placement results in a negligible increment in the amount of harvested energy, but a considerable change in luminaire efficiency. Contrary to expectations, the empirical results show that this newly-constituted configuration not only operates without affecting the illumination process but also offers increased luminaire efficiency in contrast with [6].

The proposed model also stands as an interdisciplinary effort which opens up the potential of a hybrid harvesting technology for IoT devices/services [11]. As a certain portion of energy is dissipated as heat during illumination, harvester can be structured as enabling power extraction from temperature gradients as well as electric fields. Furthermore, the lights emitted from fluorescent tubes can be also exploited if the harvester is structured with the capability of PV conversion.

By taking this potential into account it can be said that this approach can contribute to maximize the efficiency of power extraction process, as well as decreasing the level of energy wasted during illumination. We hereby obtain a unique solution that offers flexible, safe, cost efficient and interruption-free operation while providing a remarkable amount of energy, which therefore stands as a shoo-in for broadening the scope of energy harvesting communications.

VI. POSSIBLE APPLICATION AREAS OF IoT-ENABLED EFEH WIRELESS NETWORKS

For home and building area network (HAN/BAN) scenarios [32], [33], the foreseen charging time, i.e., reporting frequency, of our proposal seems quite acceptable as the executed tasks are neither mission/time critical nor high energy consuming in general, Table 3, [10]. The EFEH-powered networks structured with specialized sensors may help to prevent the wastages; minimize the losses, and increase the operational efficiencies by managing the operation of such systems like air-conditioning, heating and lighting in residential and commercial buildings. A detailed consumption profile can be constituted for both demand responsive

TABLE 3. Network requirements/specifications of some commercial wireless services [3], [32]–[34].

	Network Type	Service	Typical Packet Size (bytes)	Reporting Frequency	Tolerable Delay	Communication Technologies	Energy Source
Smart Home/Building	*HAN* *BAN*	Home Automation	10-100	15 min.	2 min.	Z-Wave, Bluetooth, ZigBee, Wi-Fi, 3G, 4G	Battery powered or energy harvester
		Building Automation	> 100	15 min.	2 min.	ZigBee, Wi-Fi, Wireless Mesh, 3G, 4G	Mains powered or energy harvester
Smart City	*NAN* *FAN*	Structural Health	100	10 min.	30 min.	802.15.4, Wi-Fi, Ethernet	Battery powered
		Air Quality Control	25-255	30 min.	5 min.	802.15.4, Bluetooth, Wi-Fi	Battery powered or energy harvester
		Noise Monitoring	255	10 min.	5 min.	802.15.4, Ethernet	Battery powered or energy harvester
		Traffic Congestion	255	10 min.	5 min.	802.15.4, Bluetooth Wi-Fi, Ethernet	Battery powered or energy harvester
		Smart Lighting	100	On demand	1 min.	802.15.4, Wi-Fi, Ethernet	Mains powered or energy harvester
		Smart Parking	150-250	On demand	1 min.	802.15.4, Ethernet	Energy harvester
Smart Grid	*WAN*	Demand Response	100	60 min.	> 5 min.	ZigBee Mesh, WiMax, Wi-Fi Mesh, Cellular	Energy harvester
		Situational Awareness	4-157	> 2 min.	1 min.	WiMax, Cellular	Energy harvester
		Wide Area Monitoring	> 52	> 2 min.	> 0.5 min.	WiMax, Cellular, Satellite communication	Energy harvester

reactions and future saving behaviors. As Table 3 suggests, the very same approach sounds also promising for the energization of widespread elements deployed in outdoor. This result accordingly encourages the establishment of low-power field, near and wide area networks (FANs/NANs/WANs), which reveals the possible coverage of all networking schemes taking part in the Smart Grid architecture [33].

Although Smart Grid vision proposes a reliable connection between a large number of diverse elements that are geographically spread [2], this connection is still a challenging issue due to the limited capabilities of existing communication protocols. At that point, insertion of newly-emerging IoT paradigm into the SG domain poses a huge potential to bring a rich set of advantages such as enhanced management and seamless interoperability, besides broad connectivity. With IoT, it becomes possible to connect evenly-distributed plethora of elements in a convenient and efficient way. The crucial data related to any system part can be transferred, when and/or where it is necessary, over the shortest link possible with a minimum expense of power and delay. The considerably enhanced communication parameters, and better coordinated and interconnected network structure facilitate the intelligent monitoring, control and maintenance of grid assets with the adaption of self-configuring versatile devices that EFEH offers.

Although the employed testbed sounds like targeting indoor applications, it can be easily adapted into outdoor systems since lighting is an essential part of daily human life. In this context, the major Smart City services, i.e., smart lighting; smart parking; traffic congestion tracking; noise, air quality and structural health monitoring [34], can be performed by EFEH-powered IoT. For example, EFEH-capable vibration, deformation, humidity and temperature sensors can sense the parameters of interest, and real-timely notify city authorities about the stress and the environmental conditions that the structures are exposed. This better forecast will eventually contribute to reduce periodic maintenance and control costs.

Instead of using bulky and sunlight-depended solar panels, EFEH-powered sensor nodes situated on field emitting streetlights can reliably measure air quality in public places. The measurements can be uploaded to a cloud-based database for public awareness. Battery-operated noise sensors can be also substituted by EFEH devices to reduce noise levels in cities at specific hours [34]. Similarly, highway lightings can be utilized to employ EFEH procedures that energize traffic congestion control mechanisms. Furthermore, the proposed method of EFEH can be also beneficial for smart lighting applications in cities. Regarding to measurements taken by light, weather, and proximity sensors, light intensities can be optimized for increased energy consumption efficiency. All these alterations are intended to make a better utilization of city resources and increasing the quality of city services, while minimizing costs and causalities, and maximizing operational efficiencies [34]. As it is revealed by the experiments, the proposed method of EFEH is able to run a majority of Smart Home/Building, Smart City and Smart Grid services. It refers that any E-field emitting light source will therefore become an integral part of these pervasive heterogeneous networks by allowing sensors to be attached conveniently. By taking into account all of these results, it can be said that this promising candidate will considerably change the operation of existing IoT-enabled Smart Home/Building, City and Grid networks in the very near future.

VII. PROTOCOL STACK REQUIREMENTS OF THE IoT-ENABLED EFEH COMMUNICATIONS

Due to the inherent limitations of EH paradigms, conventional communication architectures need to be exactingly modified as being extremely efficient. Although the EFEH methods are developed to alleviate insufficient storage

capabilities of generic batteries and/or limiting intermittency of current EH techniques, they have not been entirely utilized in the IoT domain. As our intention is battery-less execution of IoT services, existing communication technologies should be revisited to enable self-operable and self-configuring IoT networks, which requires the highly optimized versions of Internet protocols [2]. Hence, this issue necessitates reconstruction of all network layers, i.e., protocol stack of the IoT, in an energy-aware and power-efficient fashion.

A. PHYSICAL LAYER

Utilization of lighting elements for power extraction necessitates the physical layer of existing IoT networks to be rehandled as a new design problem. As this newly-emerging method is totally different from traditional battery and/or energy harvesting powered communications, new models and optimal transmission policies are highly required to maximize the throughput, reliability and quality of service (QoS).

The proposed model of EFEH is tailored to overcome the restrictions posed by the limited energy storage capabilities of wireless devices in IoT applications. Due to its diverging nature, the existing well-applied communication architectures must be restructured to make self-operable IoT networks implementable in practice. In addition, the amount of data that can be transmitted with the minimum energy harvested should be maximized to further increase the lifetime of sensor nodes.

To determine the capacity, communication channel should be modeled and accordingly analyzed by regarding the amount of energy scavenged. In addition to energy-aware coding schemes, more simpler and harvesting adaptive modulation techniques should be also investigated to provide an energy-efficient communication architecture. Less complex; more compact; and less power consumptive ultra-low power (ULP) transceivers need to be developed to boost the longevity.

B. DATA LINK LAYER

The continuous and reliable profile of the energy captured by exploiting lighting elements paves the way for perpetual data transmission, i.e., real-time monitoring, control and management activities. As the proposed method is able to offer much more energy than the existing power provision schemes by nearly acting like a continuous current source, it becomes possible to increase the transmit power (P_t) without any effect on sensor's lifetime. An increased P_t means more power to be received P_r, and an increased signal-to-noise (SNR) ratio on the receiver side. More SNR point out an increment in the channel capacity, i.e., an enhanced throughput. In addition, it can also be featured for decreasing the number of faulty transmissions, which reveals a need for the reassessment of current error control mechanisms. As a myriad of error correcting methods may become implementable depending on the accumulated energy, a detailed inspection of possible trade-offs between power consumption and reliability need to be maintained.

Since the ever-growing number of wireless devices is expected to reach to a new level with the emergence of IoT concept, unacceptable queues and delays in data transmission will be inevitable. This issue will incapacitate the spectrum, which is densely populated even now, in the very near future. To resolve this problem, previously proposed spectrum-aware solutions [35], [36] must be revisited in an energy-efficient manner.

Although the duty cycle for data transmission should be kept as low as possible due to relatively high power consumption in wake-up, listen and receive/transmit stages, the node must be responsive enough to help better anticipate a likelihood of a sudden request to ensure lossless reception/transmission of a packet. This issue necessitates tight-engineering for power-saving data link layer technologies to efficiently interconnect different IoT components.

In addition to aforementioned aspects, medium access control (MAC) stands as an another challenging issue in the realization of Internet-enabled self-sustaining wireless autonomous devices. More optimal and energy-efficient MAC protocols must be developed by regarding the capabilities of this newly-emerging energy harvesting procedure.

C. NETWORK LAYER

As addressed in Section V, a prototype is designed,fabricated and tested on a conventional ceiling type fluorescent troffer to validate the feasibility of the proposed idea. However, the nature and the corresponding illumination requirements of the residential and commercial buildings, public places, parks, and/or stadiums are envisioned, it can be mentioned about numerous types of utilizable light fixtures, i.e, a plethora of ambient E-field sources. Employment of these assets for power provision will result in a variance in the amount of harvested energy due to the variety of exploited sources' characteristics. This issue causes a very dynamic environment for routing solutions in IoT-enabled EFEH networks. Thus, network layer should be structured by considering the competence of this proposed scavenging mechanism. Energy-aware routing and delay-tolerant forwarding algorithms need to be procured.

More specifically, for data centric and flat architecture protocols, the nodes with more energy harvested should participate in the routing process. With a precise knowledge of instant energy-levels, the protocols will be able to route the data through large multi-hop topologies without any packet drops. For hierarchical routing algorithms, cluster-heads should be selected among the nodes that have the highest energy levels in their neighborhood, due to the high power demanding two-sided communications that cluster-heads are obliged to perform. This issue necessitates the consideration of energy-aware clustering mechanisms. Location-based routing algorithms in particular seems promising for EH-powered IoT applications as being energy efficient; however, delivering periodic location information might be difficult for densely-populated networks. In addition, QoS-driven routing algorithms might be also beneficial

to meet the network layer requirements of major IoT services by keeping in mind the capabilities of our proposal.

D. TRANSPORT LAYER

As the network to be structured is foreseen as a compose of heterogeneously powered devices, it is probable for a node to have inadequate energy when it is supposed to relay an upcoming datum to the next recipient. This mismatch might also occur due to the executed operation stage, deep sleep or lack of proper acknowledgment. Therefore, synchronization points out a crucial issue related to transport layer what needs to be developed as adaptive to the energy levels of network components. In addition, less power consuming transport control protocols (TCP) and energy-aware congestion detection algorithms needs to be studied.

The reliable delivery of data packets to gateways in IoT domain depends on a variety of parameters, in which the energy levels of relay nodes come to the forefront due to the diverse specs of lighting elements to be utilized. For the best performance achievable, efficient interaction between energy-aware network layers, hence cross-layer communication solutions must be investigated. They should consider the heterogeneity in the capabilities of IoT devices to propose novel algorithms that decreases energy consumption, provide seamless Internet connectivity and satisfy desired QoS requirements. Furthermore, both EH techniques and harvesting-adaptive communication protocols need to be standardized to assure the compatibility of EH devices in commercial domain, conveniently manage the network, reduce the overall heterogeneity, and mitigate the inefficiencies occurred by existing cross layer protocols.

VIII. CONCLUSION

This paper proposes a novel power provision architecture that is based on exploiting E-fields emitted by lighting elements. Fundamental requirements of IoT-enabled self-sustainable devices are addressed in both hardware and networking terms. Design aspects that maximize the harvesting efficiency are theoretically and experimentally evaluated. A low voltage prototype is outlined, structured and tested on a conventional overhead fluorescent fixture. Empirical findings disclose the potential of this proposed scavenging alternative for the applications in which greater longevity; higher robustness; and larger throughput are essential. It is believed that this effort will mitigate the energy constraints of wireless networks in the very near future by substituting the batteries without any effect on system performance. It is also envisioned that this approach will broaden the scope of energy harvesting procedures, and ease the building of self-operable IoT services.

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