

ELECTRIC-FIELD ENERGY HARVESTING IN WIRELESS NETWORKS

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ABSTRACT

Electric-field energy harvesting (EFEH) can be considered as an emerging and promising alternative for self-sustainable next-generation WSNs. Unlike conventional harvesting methods that rely on ambient variables, EFEH provides more reliable and durable operation as it is operable with any voltage-applied conductive material. Therefore, it is better suited for advanced throughput and applications requiring a certain QoS. In this article, we introduce this newly emerging WSN paradigm, and focus on enabling EFEH technology for smart grid architectures, such as home, building, and near area networks, where the field intensity is relatively low. To this end, a practical methodology and a general use implementation framework have been developed for low-voltage applications by regarding compelling design issues and challenging source scarcity. The proposed double-layer harvester model is experimentally evaluated. Its performance in terms of implementation flexibility, sensor lifetime, and communication throughput is investigated. In addition, current challenges, open issues, and future research directions are discussed for the design of more enhanced EFEH wireless networks.

INTRODUCTION

The ubiquitous structure of wireless sensor nodes has markedly altered monitoring and surveillance systems, and accelerated the utilization of wireless sensor networks (WSNs). To ensure high-accuracy data collection and enhanced communication quality, sensors can even be deployed in the thousands. However, energizing these excessive numbers of sensors can constrain the performance of the communication. Although the majority of wireless nodes operate discontinuously, a typical battery tends to deplete within a year. Therefore, an auxiliary or distinct power source must be employed. To avoid battery deployment, heat, electromagnetic, and kinetic energy come into prominence to run the nodes autonomously.

Even though the harvesting methods are broadly comparable in cost and lifetime with commercial general use batteries, the power to be extracted by harvesting might not always be continuous, and its magnitude may alter markedly depending on the ambient factors. These issues have directed research efforts to find more reliable sources in terms of energy availability and endurance. In this regard, electric-field stands as

the most promising candidate with the characteristics of ambient variable independence, sufficient power rating, low complexity, and excellent energy continuity.

Electric-field energy harvesting (EFEH) is first proposed for high and middle voltage (HV/MV) overhead power lines by considering the surrounding electric field in abundance. The empirical results revealed the competence of EFEH in providing advanced situational awareness and increased asset security, which accordingly motivated the utility companies to utilize it. As one of the main purposes of the smart grid (SG) concept is to consume the available energy as efficiently as possible [1], EFEH wireless networks seem promising to prevent waste, minimize loss, and increase operational efficiency. The networks structured with specialized sensors, such as light, temperature, humidity, and presence, can also sense an indoor environment, process the gathered parameters, and notify an upper-level authority for decision making procedures. By this means, such systems as air conditioning, heating, and lighting can be deactivated in the case of no human presence or when they no longer need to operate. Accordingly, a detailed consumption profile can be constituted to both notify the utility for demand-response management and guide the customer for future saving behaviors.

Although there are already some preliminary efforts to implement EFEH in low-voltage systems, there is currently no study intended explicitly to build wireless networks by regarding the varying energy needs of differentiated network components. We therefore focus on how to optimize the design of the harvester for supporting vast network topologies by allocating different levels of power and to meet the requirements of specific applications. For this purpose, we propose a multi-layer harvesting model and a practical, general-use implementation framework by elaborating on the current challenges of this fundamentally new networking paradigm to enable sensor energization in smart home, smart building, and SG scenarios.

The remainder of this article is organized as follows. We commence with a literature review of existing energy harvesting techniques. Then we extend our study to the basic principles of EFEH including its basis, main constraints, and applicable procedures. In the next section, we point out the issues related to low-voltage application, and propose a multi-layer harvester model to increase

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	Characteristics	Energy density	Advantages	Disadvantage	Literature
Solar	Ambient, uncontrollable, predictable	15 – 100 mW/cm ²	Environmental, independent of grid, high output voltage	Not always available, sensitive structure, deployment constraints	[2, 4–6, 8]
Thermal	Ambient, uncontrollable, unpredictable	≈ 50 μW/cm ²	Environmental, independent of grid, scalable	Not always available, requires efficient heat sinking	[2, 4, 8]
Airflow	Ambient, uncontrollable, unpredictable	1 mW/cm ²	Environmental, independent of grid, available day and night	Fluctuating density, hard to implement, requires construction	[2, 5, 8]
Motion	Non-ambient, controllable, unpredictable	330 μW/cm ²	No ext. power source, compact configuration, lightweight	Charge leakage, depolarization, highly variable output	[2, 4, 8]
RF	Non-ambient, uncontrollable, predictable	1 μW/cm ²	Abundant in urban areas, allows mobility	Scarce in rural areas, low power density, distance-dependent	[2–4]
M-Field	Non-ambient, controllable, predictable	150 μW/cm ³	No ext. power source, easy to implement, non-complex structure	Requires high and perpetual current flow, safety vulnerabilities	[4–6, 8]
E-Field	Non-ambient, controllable, predictable	NA	No need for current flow, easy to implement, always available	Being capacitive, mechanical constraints	[4–14]

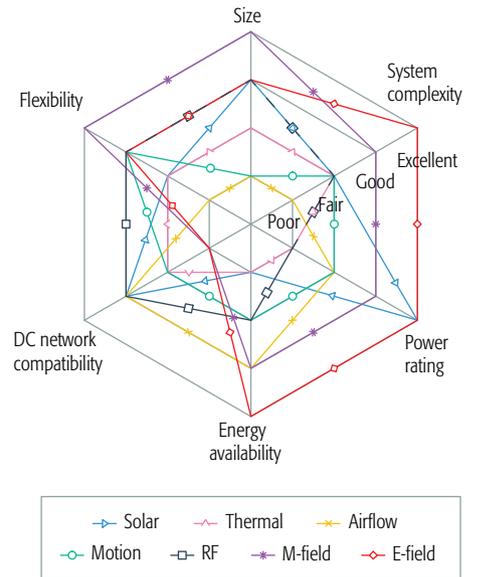


TABLE 1. Comparison of the existing energy harvesting techniques.

the power to be scavenged with negligible cost and volume increments. This is followed by the performance analysis and a detailed discussion of our proposal. Since this emerging method is still in its early stages, open issues, technical challenges, and future research directions are addressed. Finally, we conclude the article.

EXISTING ENERGY HARVESTING TECHNIQUES

Existing energy harvesting architectures are categorized into two groups in [2], where *harvest-use* means demand-based, and *harvest-store-use* refers to availability-dependent scavenging techniques. Likewise, potential harvestable sources are broadly classified as controllable and uncontrollable by this work. By regarding this separation and the frequency of preference, some leading harvesting techniques are discussed, and a detailed comparison is illustrated in Table 1.

Solar Energy Harvesting: For the monitoring of overhead power lines, solar cell inlaid photo-voltaic (PV) panels are utilized for converting solar energy into electricity [2, 4]. Although these systems offer sufficient solutions in terms of power rating, complexity, and availability, harvested energy is affected by highly time-varying and somewhat random sunlight conditions [5]. Besides the dramatic fluctuations in output power, installation and maintenance costs come forward as the main shortcomings of this technique [8]. For indoor applications, specialized PV materials for taking advantage of the rays emitted from light fixtures are used.

Airflow/Motion-Based Energy Harvesting: Wind turbines, and on a smaller scale anemom-

eters and piezoelectric materials, are being developed for kinetic energy conversion [2, 4]. Since the airflow energy (i.e., wind power) enables wide-scale communication networks structured in open space, its performance is threatened by environmental variables similar to solar energy-based approaches. Due to the lack of airflow in closed areas, piezoelectric materials become an alternative for attaining energy from highly random and mostly unpredictable external-factor-based motion variations to drive low-power-consuming wireless devices [8].

Thermal Energy Harvesting: Thermoelectric generation is an innate power provision technique for smart grid communications, in which temperature swings between the power line and the environment are used to extract energy [2]. Similar to wind and solar energy related efforts, it depends on ambient variables, and therefore may fail to harness stable power in some cases. For less power requiring sensor nodes, peltier/thermoelectric coolers and thermocouples, which perform satisfactorily, are mostly preferred for building delay-tolerant wireless networks.

Electromagnetic Wave/RF Energy Harvesting: Regarding the intensive use of GSM networks in urban areas, RF signals have attracted harvesting interest in recent years [2]. RF energy harvesting is simply based on collecting RF signals emitted from cell phone towers by using large aperture power receiving antennae, and then converting them into utilizable DC power for the sensor nodes. Even though this method serves reliable solutions regardless of the environmental variables, the necessity of close deployment of receiver antennae to network transmitters and the fact that it provides quite low power density

E-field energy harvesting is the only method that has the capability of operating systems at any time that the power line is on. In other words, notwithstanding the ambient factors, harvesting energy from the field is always possible if there is voltage potential on a conducting material.

gained from an unpredictable source compel its utilization in time-critical applications with extensive computation workloads [3, 4].

Magnetic Field Energy Harvesting: In addition to the aforementioned approaches, wireless networks can also be operated by exploiting electromagnetic fields around the current carrying conductors [4, 6]. To do that, current transformers are employed to gather energy from the ambient M-field by clamping around the power cords. This technique provides an adequate rate of power and less complex utilization. However, the availability of energy is affected severely by the current density on the transmission line. Since the M-Field occurs due to AC current, the line must be loaded to allow sufficient current flow. However, when the amount of current drained by the household appliances is considered, it can be said that this method has limited applicability in home area networks (HANs).

Electric Field Energy Harvesting: EFEH is the only method that has the capability of operating systems at any time the power line is on. In other words, notwithstanding the ambient factors, harvesting energy from the field is always possible if there is voltage potential on a conducting material [4–14]. That makes EFEH the most viable option for sensor energization in the sense of availability, predictability, and controllability.

ELECTRIC FIELD ENERGY HARVESTING

Regarding the basic principles of electrostatics, any conductor energized at some voltage level has a radial E-field. For AC lines, this time-varying field produces a displacement current that can be expressed with Maxwell's equation,

$$I_d = \epsilon \int_s \frac{d\mathbf{E}}{dt} \cdot d\mathbf{s} \quad (1)$$

where ϵ is the permittivity and \mathbf{E} is the electric field intensity. The electric field emitted around the voltage applied material can be transferred capacitively via I_d to charge an apposed capacitor. The energy stored in this capacitor can be stated as

$$E = \frac{1}{2} CV^2 \quad (2)$$

where C is the capacitance and V is the voltage accumulated. As this energy is scavenged from the ambient electric field induced by the energized conductor, this method can be defined as EFEH [4–14].

Since the counterparts of this technique depend strongly on environmental conditions, grid-based variables, or any other uncontrollable parameters, EFEH can be considered as the most promising way to compose long-term and self-sustainable communication systems. Because the voltage and frequency are firmly regulated and exactly maintained, the E-field is therefore stable and predictable in its behavior. Initial experiments revealed the potential of EFEH in providing enhanced condition monitoring for SG operations, with a constant rate of scavenged power, satisfying quality of service (QoS), and cost effectiveness. These factors have attracted research efforts focused on this reliable and viable alternative to build self-sustainable HANs and building area networks (BANs). Such networks are

destined to interconnect household appliances, smart meters, and wireless sensor nodes in order to support remote surveillance, control, and management operations. As the tasks to be fulfilled are not mission-critical, the communication infrastructure between the HAN/BAN devices can be governed with low-data-rate, low-bandwidth, and short-distance technologies. This reason in particular paves the way for EFEH adoption to HANs and BANs. As a consequence, SG applications are extended into home and building premises to provide advanced energy management policies, and demand responsive reactions.

For outdoors, the reliability of the grid is an ongoing challenging issue for all utility companies. To maintain the desired operation, solutions including enhanced situational awareness have received significant attention, and a plethora of approaches have been proposed for grid-wide remote monitoring, control and diagnosis. Preliminary work related to this emerging topic was initially conducted on MV/HV overhead transmission lines, as shown in Fig. 1, by considering the surrounding E-field abundance formed by excessive levels of voltage.

As a result of high tension presented on the operation area, it was required to eliminate sharp corners to avoid possible drawbacks related to air ionization-based partial discharges. That necessity resulted in tube and/or donut-shaped edge collocations in harvester design, as depicted in Figs. 2a and 2b. The insertion of the harvester results in serially connected two capacitors, i.e., a capacitive voltage divider, where C_1 and C_2 represent the equivalent capacitances from power line to harvester, and harvester to earth, respectively. As seen in Fig. 2c, the leakage electric field is confined in a storage capacitor C_s after rectified by diodes. The given switch model corresponds to an autonomous connection circuit (ACC) to be utilized for interchange between operation modes.

The theoretical concept of EFEH is first proposed in [4] to enable monitoring of power lines against aliasing effects such as sagging, icing, vibration, and corrosion. The performance of EFEH is further elaborated in [5], and the experimental studies disclosed the availability of continuous power. A new model based on circular metallic plates is constituted in [6], where [7] represents a multi-layer harvester as an alternative design procedure. In a similar study, a cylinder-shaped scavenger investigates the energy availability with respect to capacitance variation [8]. As opposed to existing efforts in the area, two distinct proposals are tailored to build battery-less wireless SG networks. In [10], a rectangular harvester is proposed to provide ease of utilization, where [9] includes embedding an electrode in a power line insulator to ensure more secure operation.

Although there exist several possible approaches proposed for HV/MV, none of them fits perfectly into the low-voltage systems, mostly due to size constraints and source scarcity. To make low-voltage EFEH wireless networks more applicable, the main requirements, i.e., a totally specialized harvester and more efficient circuit design, enhanced power management and communication architectures, are discussed below as taking account of the existing efforts in the area [11–13].

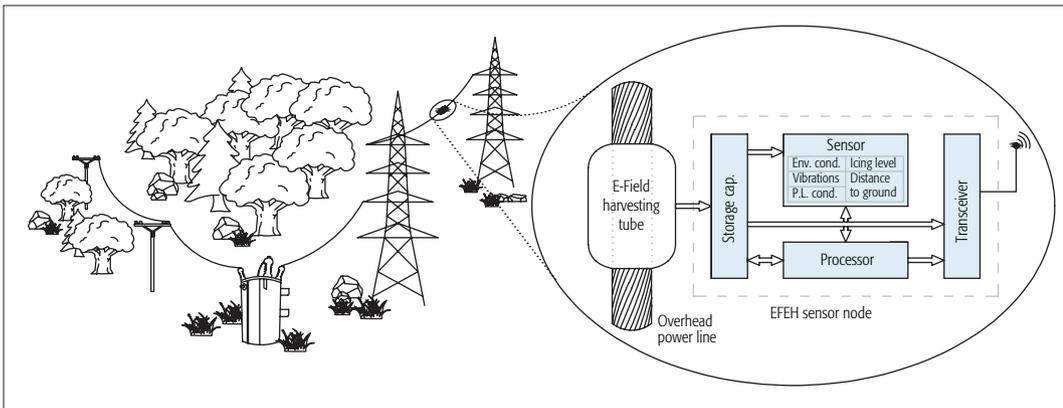


FIGURE 1. Practical model diagram of EFEH sensor nodes deployed on the overhead power lines.

LOW-VOLTAGE EFEH WIRELESS NETWORKS

In [10], the authors have claimed that the EFEH concept might not be a feasible option on low-voltage considering the potential design problems. However, forward research efforts, [11, 12] and [13], experimentally invalidated this claim. In [11], the authors achieved to extract $47 \mu\text{W}$ of power with a 60 cm long piece of aluminium foil stuck on a 220V AC power line. The proposed method ensures sensing, processing and transmission of temperature data every 42 seconds. This effort mainly focused on the adoption of low-leaky and low power consumptive micro-electromechanical systems (MEMS) to enhance the switching performance. A similar approach is rehandled in [14] to drive ZigBee-based sensor nodes. The 60 cm long harvester, specialized for two-wire power cords, is able to extract $1.4 \mu\text{W}$ of power from a 100V AC supply. The gathered energy is utilized for building an energy management system that notifies an operator every 250 seconds.

In addition to conductor mounting-based proposals, fluorescent tubes can also be considered as an alternative source of E-field, and a corresponding configuration for the low-voltage EFEH techniques. The model given by [14] describes a scavenging paradigm including copper panels placement under fluorescent fixtures with a certain separation. It is claimed that roughly 200 mW of power can be harvested from the ambient field, which will be regulated by an IC, namely LTC3588-1, to acquire stable and continuous voltage for the sensor nodes.

LOW-VOLTAGE EFEH CONCEPT AND THE APPLIED PROCEDURES

The main objective of the model given in Fig. 3a is to drain I_d and collect the charges in C_s , until the stored energy becomes sufficient for sensing, processing, and transmission. In other words, the conductive sheath obstructs the outward flow of the ambient E-field, and concentrates it into C_s . The diodes, D_1 and D_2 , are used for both rectifying the alternating current, and preventing the scavenged energy from back feeding. Since the gathered energy is mostly limited, further efforts

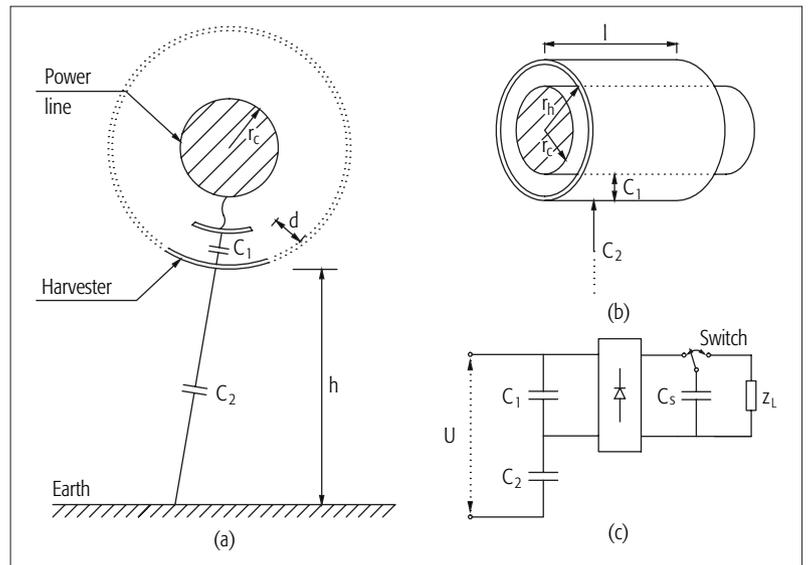


FIGURE 2. a) Cross section of the two-plates concept, and the capacitive voltage divider dispersion; b) side view of the tubular E-field harvester; c) equivalent circuit of the EFEH system.

should be focused on utilizing low loss rectifiers, power saving micro-controllers, and more efficient regulators, because any reduction in the amount of energy consumed for system operation will directly increase the sensor lifetime, which will eventually contribute to overall communication reliability. It is also essential to enhance the energy storage capabilities for increased longevity, where quick-charged, long-lasting, and high power condensed super capacitors become crucial.

An ACC, called a 'Switch' in Fig. 3c, needs to be utilized to switch between operation modes, and regulate the energy usage. It autonomously enables charge transfer when the energy is high enough for transmission, and turns off the circuit for the next harvesting period when the voltage descends below a threshold value. This action not only prevents redundant and undesired discharge of C_s to 0 V, but also allows more frequent data transmissions by shortening the charging time. The other feature that is being ensured by the ACC is isolating the nodal circuitry from the electric grid. Since the harvester is structured as exploiting the grid induced E-field, any load attached in huge impedance may affect the mains shape, and result in irregularities or even failures. The ACC there-

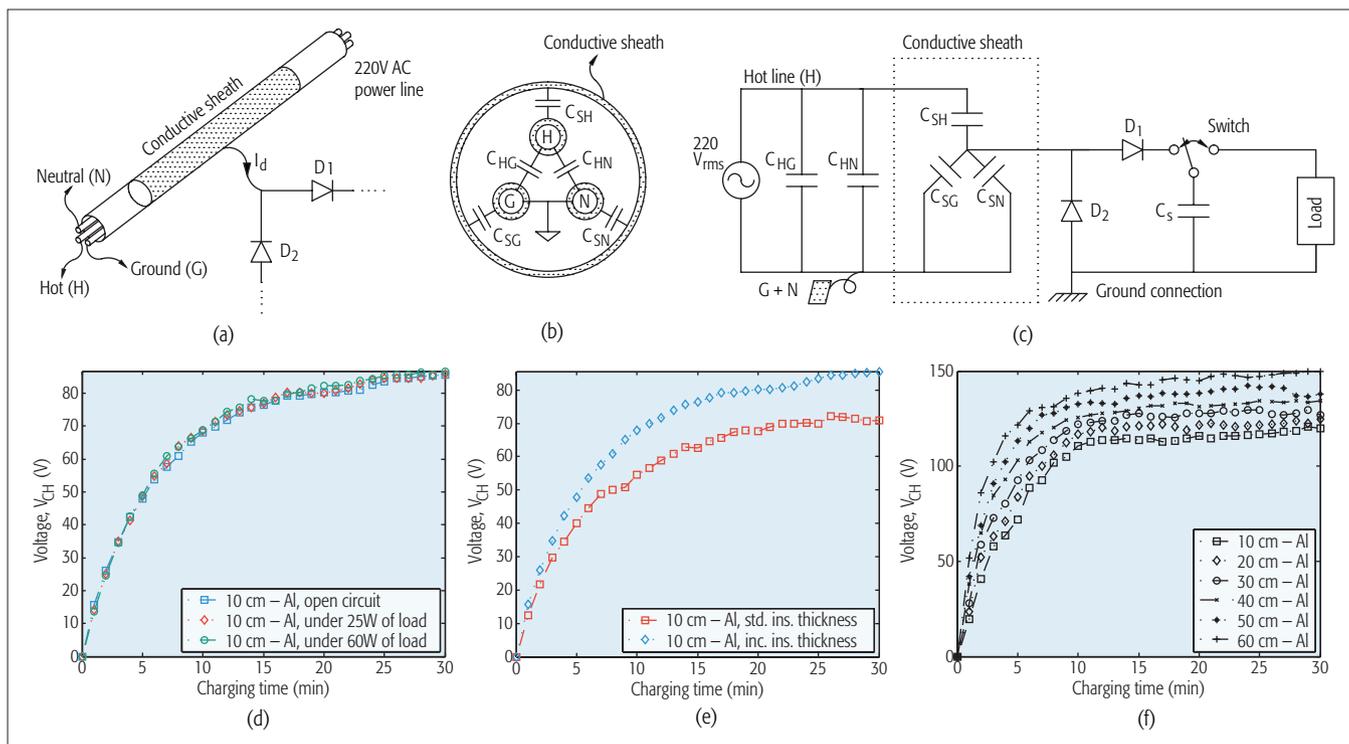


FIGURE 3. a) Low-voltage EFEH concept; b) depiction of sheath wrapping resultant stray capacitors; c) equivalent circuit diagram of the low-voltage EFEH concept; d) charging pattern of C_s with respect to the attached loads; e) charging pattern of C_s with respect to insulator thickness, under no load; f) charging pattern of C_s with respect to sheath length, under no load (i.e., open circuit condition).

by takes the node apart from the harvester, and avoids current drawings from the grid itself. As the safety concerns are resolved, proper operation of the related systems is also ensured.

In principle EFEH is expected to operate on even a no-load/open-circuit AC power line, in which conduction current does not flow. In such a case, the EFEH concept may be an outstanding solution to build WSNs without any constraints. Fig. 3d represents corroborative findings we obtained, where the voltage gathered increases evenly in every case, i.e., under no load, 25 W, and 60 W of loads. This result encouragingly implies that EFEH enables charge extraction regardless of the line current, which makes it more competent against its similar-principled closest pursuer M-field-based counterparts.

APPLICABLE TECHNIQUES FOR ENHANCED PERFORMANCE

Along with the electric field intensity, the dimensions of the harvesting device, the effectiveness of the equipped components, the duty cycle of the sensor node, and the protocol suite to be structured are the factors that affect the performance of the low-voltage EFEH wireless networks. We hereby highlight some issues that relate to more efficient system operation, in the aspects of both design and communication.

Design Parameters: The basics of capacitors implies that it is possible to collect more charge by enlarging the insulator diameter. Because the capacitance increases proportionally with the thickness of the insulator, and the higher capacitance means the more charge to be stored. As seen in Fig. 3e, when the thickness is altered from

0.77 mm to 1.3 mm while keeping the length constant, the gathered voltage increases by 20.9 percent for the same time period. This result states that the scavenged energy can be augmented notably for a small increment in the harvester volume.

As opposed to the statement claimed in [12], it is not accurate to explain the reason that lies behind preferring copper tape instead of aluminium foil so as to provide ease of control and tight coverage, because the scavenging performance is directly associated with the electrical characteristics of the material that forms the harvester. The measurement results in Fig. 4d show that copper outperforms aluminium by collecting more charges, approximately 15 percent more, in the same charging period. In other words, more frequent data transmission can be enabled since the time spent in the harvesting stage is further reduced.

Communication in EFEH Wireless Networks: As well as the harvester-based modifications, communication related issues should also be regarded to maximize the system performance. In this context, less complex, more compact, and less power consumptive ultra-low power (ULP) transceivers are required. Simpler modulation techniques need to be employed to obtain a more enhanced physical layer. Furthermore, an optimized signal waveform and bandwidth should be utilized to maximize the power transmission efficiency.

Since the considerable part of the duty cycle is exerted for power extraction, it is probable that a node might still sit in the harvesting stage when it is supposed to relay an upcoming datum to the next recipient. Therefore, synchronization points out a crucial issue related to transport layer that needs to be studied further for more optimal

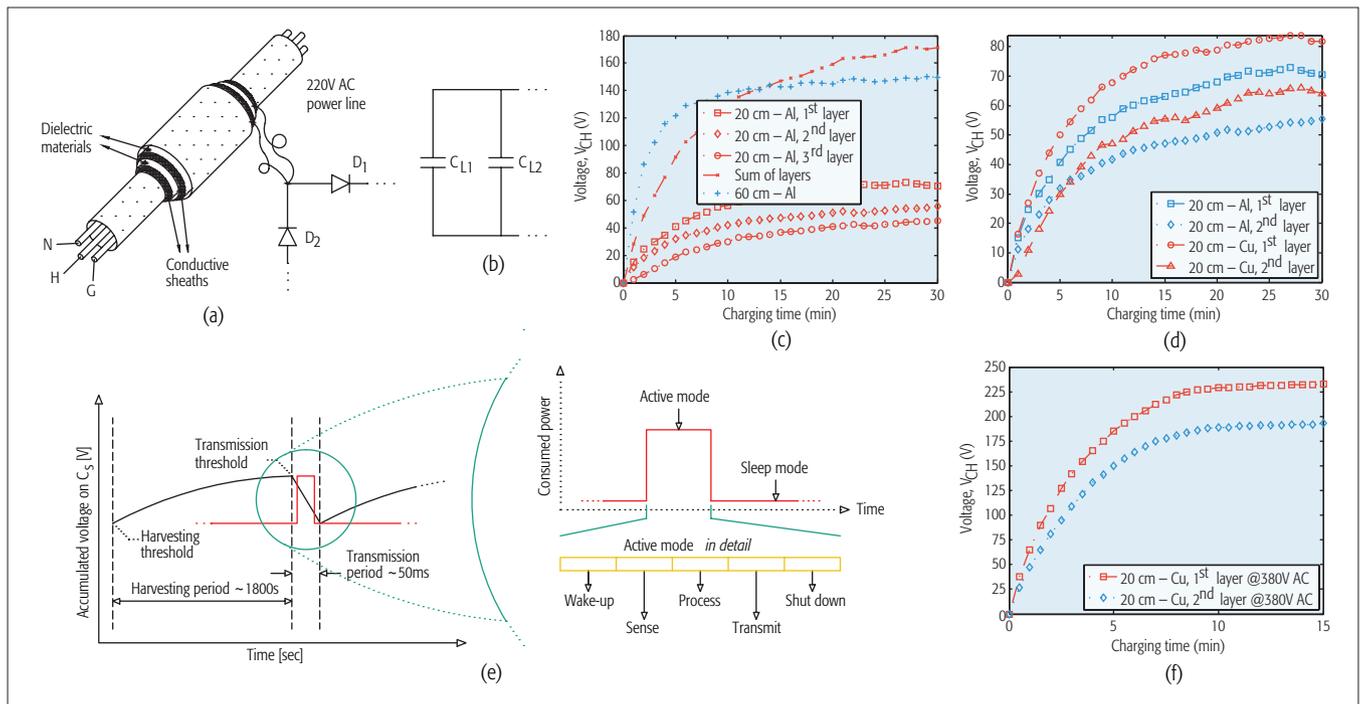


FIGURE 4. a) Representative depiction of multi-layer concept; b) resulting circuit diagram of double-layer model; c) comparison of single and double-layer formations, under no load condition; d) comparison of double-layered Al and Cu utilization, under no load condition; e) operation cycle of the proposed EFEH architecture; f) charging pattern of multi-layer structure, performed on 380 V AC line.

medium access control (MAC) protocols. In addition, the network layer must be structured keeping in mind the capabilities of this completely new energy scavenging architecture. Energy-aware routing and delay-tolerant forwarding algorithms need to be procured. In conclusion, for the best performance attainable, effective interaction between these layers, hence cross-layer communication solutions, must be investigated [3].

MULTI-LAYER HARVESTING STRUCTURE

Differentiated sensors in terms of duty cycle and circuitry tend to drain power supplies at different rates depending on their tasks. More specialized nodes may require multiple batteries or power provision systems to extend the operation time for aggregation, signal processing, multi-hopping, and maintenance. However, considering the aim of providing as much energy as possible at the smallest cost, volume, weight, and recharge time, extra battery deployment may not be an option in every case. In this manner, the performance of the chosen harvesting paradigm ought to be enhanced as far as possible. As Fig. 3f suggests, harvester length should be increased as much as possible to extract more power from the field. However, this is not always applicable, because the wires deployed are generally non-fixed and/or the available parts are not long enough. These constraints inspire the idea of vertical expansion instead of horizontal increment. To this end, a multi-layer harvesting model is constituted as shown in Fig. 4a. After adding a second layer of copper, the harvester is altered to two capacitors connected in parallel, as seen in Fig. 4b.

In contrast with the statement claimed in [12], experiments revealed the ongoing E-field presence surrounding the wrapped area. Figure 4c illustrates the related results, and compares the

performance of single-layer and triple-layer formations. As shown in the figure, the parallel connected second layer, i.e., the capacitor formed, C_{L2} , collects more than two thirds of the voltage at the same time in regard to the first capacitor, i.e., C_{L1} . Therefore, the empirical findings show that harvesting considerably more energy with negligible volume and cost increments is practically attainable. In light of this result, the double-layer structure can be considered a promising solution for energy-constrained WSNs. It is expected to play a key role to operate more power requiring sensor nodes, and therefore support numerous network topologies to be structured.

PERFORMANCE EVALUATION AND DISCUSSION

As stated, the proposed concept motivates ULP transceiver utilization. In this regard, NXP's JN5148 [15], a ULP wireless MCU, is assumed to be employed. This chip operates at 3 volts, draws 15 mA of current during transmission, and consumes far less of it, on the order of μA , while sleeping. Now consider a delay-tolerant network scenario structured in a star topology, where the chip, i.e., JN5148, transmits data to a network coordinator every 15 min. Total time exerted for wake-up, sense, process, and transmit stages is assumed to be around 50 ms. As depicted in Fig. 4e, the node will stay in sleep mode during the harvesting stage, and wake up immediately when the voltage on C_s exceeds the transmission threshold. The ACC roughly consumes 65 μJ of energy for switching the operation to active mode. The node right after exhausts the stored energy up to 2 μJ for sensing various parameters of interest. Then the gathered information is processed and transmitted to a higher authority. The node

Experimental results imply that the EFEH is a promising solution to build WSNs with greater longevity; higher robustness; larger throughput; and improved flexibility, which opens up the potential of distributing more sensors, and enabling more parameters to be gathered conveniently.

	Protocol	Radio chip	Freq. [GHz]	Range	D. rate	RX/TX [mA]	Sleep	Supply	Req. energy
IRIS	ZigBee	AT86RF230	2.4	25 m	250 kb/s	16/8	8 μ A	2.7–3.3 V	25 mJ
MicaZ	6LoWPAN	CC2420	2.4	30 m	250 kb/s	19.7/17.4	15 μ A	2.7 V	28 mJ
Jennic's	ZigBee	JN5148	2.4	1 km	550 kb/s	17.5/15	1.5 μ A	3 V	4.5 mJ
WAVIoT	NB-Fi	CC1310	0.868/0.915	16.6 km	100 kb/s	9.9/44	12.5 μ A	3.3 V	39 mJ
Sigfox	UNB	ATA8520	0.868/0.915	10 km	100 bps	20/49	15 μ A	3.6 V	45 mJ

TABLE 2. Comparison of the most preferred wireless networking chipsets/technologies.

consumes roughly 3.8 mJ of energy to fulfil these tasks. After receiving acknowledgement packets, it turns back to sleep mode, and the ACC drives the circuit to the next harvesting period. The resulting consumption is said to be around 4.5 mJ. A representative depiction of this operation, i.e., the duty cycle of the EFEH system, is illustrated in Fig. 4e.

As the proposed system is suitable for any voltage applied conductor, preliminary experiments were performed with a commercial household extension cable without any loss of generality. As seen in Fig. 4d, 20 cm long double-layered copper sheaths store 12 mJ of energy in a 2.2 μ F capacitor in 15 min when there is no load attached to the line. This finding and the result of the planned network scenario reveal that a fully charged EFEH sensor node can perform even better than a battery-operated equivalent under certain conditions. When the portion of the harvested energy to be consumed is regarded, it is seen that the nodes will still have enough power to make additional transactions. This issue paves the way for utilizing routing protocols as well as point-to-point topologies.

As the scavenged energy is theoretically unlimited with the proposed method, any increment in transmitting power (P_t) will not affect the sensor's lifetime. Regarding this idea and the amount of gathered energy, which is 12 mJ, unused power can be utilized for increasing P_t , which will eventually increase the power on the receiver side (P_r). A greater P_r means a greater signal-to-noise (SNR) ratio to be attained. Since the bandwidth does not change, more SNR yields increased channel capacity, which provides enhanced throughput. Depending on the application needs, this energy, i.e., the altered SNR, can also be featured in error control. Alternatively, residual energy can be consumed to increase the number of transmissions for either enabling more data to be obtained or recovering faulty transactions. These considerations point out an optimization problem that needs to be studied to determine the best trade-off between the transmit power, data rate, packet size, and/or operation time for maximizing the performance.

When the requirements of HAN and BAN oriented scenarios are envisioned, 15 min. of informing time is acceptable since the networks structured are not mission critical [1]. This is also valid for the outdoor applications, where the very same approach can be performed for the energization of widespread elements. Regarding this fact, we have slightly changed our configuration to also make it suitable for 3-phase 380V AC operative assets deployed in any small-scaled industrial, medical, and educational facilities. The following experiments revealed that it is possible to scavenge

roughly 100 mJ of energy in 15 min as shown in Fig. 4f. This result accordingly encourages the establishment of low-power wide area networks (LPWANs) [16] besides HANs and BANs. As summarized in Table 2, all the wireless devices evaluated require less energy than what is obtained, so that the battery-less communication of both low-power wide-area radios (WAVIoT and Sigfox) and conventional wireless sensor nodes (IRIS and MicaZ) can be guaranteed by our double-layer EFEH model for the constituted network scenario. By using EFEH-enabled Internet-capable sensors, direct transmission of the measurement data to a SCADA-like backhaul system can be ensured. As the advanced control of the operation area is enabled, this better coordinated operation will eventually help achieve more reliable, secure, and inter-operable communication architectures. By taking into account all of these results, it can be said that the EFEH is a promising candidate to considerably change the operation of existing wireless SG networks in the very near future. Powering the sensors by exploiting ambient sources will eventually reduce the potential power flows, increase the energy consumption efficiency, make a good impact on the environment, and therefore contribute to the aims of the smart grid vision.

CONCLUSIONS

In this article, we have presented a comprehensive review of EFEH proposals, and focused on how to implement the existing methods on low-voltage to enable self-sustainable smart home, smart building, and smart grid architectures. A novel methodology and corresponding guidelines have been provided for the design of a more enhanced harvesting procedure. Experimental results imply that the EFEH is a promising solution to build WSNs with greater longevity, higher robustness, larger throughput, and improved flexibility, which opens up the potential of distributing more sensors and enabling more parameters to be gathered conveniently. It is believed that this method alleviates the bottlenecks of energy-constrained WSNs, and will broaden the scope of energy harvesting mechanisms in the very near future.

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