Energy Harvesting and Wireless Transfer in Sensor Network Applications: Concepts and Experiences

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Advances in micro-electronics and miniaturized mechanical systems are redefining the scope and extent of the energy constraints found in battery-operated wireless sensor networks (WSNs). On one hand, ambient *energy harvesting* may prolong the systems' lifetime or possibly enable perpetual operation. On the other hand, *wireless energy transfer* allows systems to decouple the energy sources from the sensing locations, enabling deployments previously unfeasible. As a result of applying these technologies to WSNs, the assumption of a finite energy budget is replaced with that of potentially *infinite*, yet *intermittent*, energy supply, profoundly impacting the design, implementation, and operation of WSNs. This article discusses these aspects by surveying paradigmatic examples of existing solutions in both fields and by reporting on real-world experiences found in the literature. The discussion is instrumental in providing a foundation for selecting the most appropriate energy harvesting or wireless transfer technology based on the application at hand. We conclude by outlining research directions originating from the fundamental change of perspective that energy harvesting and wireless transfer bring about.

CCS Concepts: • **Computer systems organization** → *Sensor networks*; *Embedded hardware;*

Additional Key Words and Phrases: Wireless energy transfer, energy harvesting

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1. INTRODUCTION

Wireless sensor networks (WSNs) have become a viable tool to gather information from the environment and to act on it non-invasively. Typical deployments employ battery-powered nodes. As a result, a whole body of work appeared to provide staple networking functionality within limited energy budgets. Simultaneously, as the form factor of WSN nodes shrunk, the battery size had to reduce as a consequence. Notwithstanding recent developments in battery fabrication, this resulted in increasingly smaller amounts of available energy.

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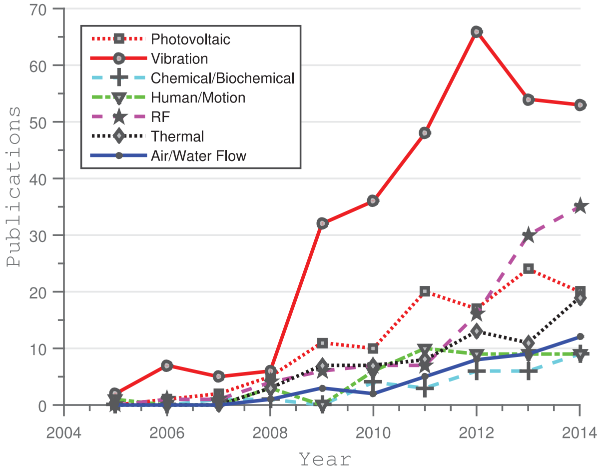

Fig. 1. Number of journal articles published by ACM, IEEE, or Elsevier isince the mid-2000s revolving around micro-level energy harvesting.

Energy harvesting and wireless transfer. To counteract this trend, recent advances in micro-electronics and miniaturized mechanical systems are finding their way in WSNs along two lines. On one hand, technologies to *harvest energy* from the ambient may integrate with WSNs to prolong the system's lifetime or to enable perpetual operation whenever possible. A variety of techniques appeared that apply to, for example, light, vibrations, and thermal phenomena, while matching the constraints of common WSN nodes. These technologies are naturally attractive wherever replacing batteries is unfeasible or impractical, as in biomedical implants [Chou et al. 2010].

The applicability of energy harvesting remains a function of the deployment environment. Depending on its characteristics, suitable sources of ambient energy may simply not be at disposal. Several scenarios also bear constraints on node locations that render the benefits of energy harvesting not able to pay back the additional complexity and costs. For example, WSN nodes equipped with light sensors are employed to realize adaptive lighting in road tunnels [Ceriotti et al. 2011]. Potential sources of ambient energy are lacking in this environment, thus the opportunities for energy harvesting are minimal. However, the nodes cannot be re-arranged in space to favor energy harvesting, as their locations are dictated by application requirements.

The issues above mainly stem from the coupling between the location of energy harvesting and where sensing needs to occur. *Wireless energy transfer* (WET)—that is, the ability to move energy across space—can break such coupling, allowing WSN designers to exploit abundant energy sources available at places other than the locations of sensing. In addition, WET may distribute the available energy from energy-rich locations to energy-poor ones, improving the overall energy balance. Several techniques recently have appeared that enable WET in WSN applications as well, such as laser [Bhatti et al. 2014], power light-emitting diodes (LEDs) [Liu et al. 2013a], or radio transmissions [Buettner et al. 2008; PowerCast 2009]. Notably, energy harvesting is an integral part of WET, as the latter occurs by intentionally spreading energy in the ambient, which is gained back at the receivers' end using harvesting techniques.

Energy harvesting and wireless transfer fundamentally redefine the traditional design assumptions in battery-operated WSNs: from considering a *finite* energy budget to relying on an *infinite*, yet *intermittent*, energy supply. This change of perspective spurred a plethora of research works. As an example, Figure 1 depicts the number of articles published since the mind-2000s in ACM, IEEE, and Elsevier journals dealing with micro-level energy harvesting, that is, the kind most directly applicable to WSNs. The figure accounts only for the lowest-level enabling technology and does not include, for example, works about network protocols in energy harvesting scenarios. The overall trend is markedly *increasing*.[1]

Prior literature. Because of the growing interest, a few surveys about energy harvesting and wireless transfer recently have appeared. These may be broadly classified into three categories.

A few works mainly focus on integrating energy harvesting into the *node* design; for example, by discussing different energy storage solutions possibly coupled with WSN nodes [Sudevalayam and Kulkarni 2011; Kausar et al. 2015]. However, low-power embedded technology is quickly evolving, and *both* complete uW-level platforms [Kuo et al. 2014] and 32-bit Microcontroller Unit with standby currents of a few hundred nA [Ko et al. 2012] are appearing. Thus, the state of affairs is in a situation of rapid change.

Other works discuss similar aspects for WET and yet without explicitly linking it with energy harvesting. For example, Akhtar and Rehmani [2015] investigate the use of super capacitors as opposed to rechargeable batteries, whereas Xie et al. [2013] describe a history of WET together with considerations on how to leverage the omnidirectionality of electromagnetic radiations to power WSNs. Similarly to the above, these considerations are likely to be a function of currently available embedded hardware, which is quickly evolving.

Special attention is devoted to WET through radio-frequency (RF) transmissions. Visser and Vullers [2013] study the feasibility of RF-based WET, as well as the hardware design and dimensioning of systems to match exposure limits in specific application scenarios, such as smart buildings. Bi et al. [2015] as well as Lu et al. [2015] specifically report on systems based on the “harvest-then-transmit” paradigm, employed by Radio-frequency identification-scale devices to operate in a battery-less fashion. The authors discuss circuit models, signal processing techniques, and network architectures, reaching into systems that combine energy and data transfer in the same waveform.

Contribution and roadmap. In contrast to prior literature, we aim at providing an in-depth, yet intuitive understanding of the *phenomena* enabling energy harvesting and wireless transfer. Further, unlike works that only focus on one or a few technologies [Visser and Vullers 2013; Bi et al. 2015; Lu et al. 2015], our goal is to comprehensively cover *multiple technologies*. This allows us to elicit the relations and complementary aspects of energy harvesting and WET, while creating a foundation to analyze the tradeoffs of different technologies and compare them against each other. Our investigation is instrumental to the selection of the most appropriate solution based on *application* requirement. In contrast to trends in embedded hardware, the relation of energy harvesting and wireless transfer to an application’s traits is likely far less volatile. We therefore expect our analysis to enjoy long-term validity.

In this article, we limit ourselves to the lowest-level technology that enables energy harvesting or WET. Other works that are not specific to a given energy harvesting or WET solution, such as network protocols for rechargeable WSNs or scheduling algorithms for mobile recharging stations, are often generally applicable regardless of the

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[1] Figure 1, which is only taken as an example of the trends at stake, solely considers journals as they constitute a well-defined (sub)set of publication venues. This is certainly not comprehensive but representative of the growing interest in the topic. Accurately identifying relevant articles at other venues, such as conferences, would likely be more difficult and arguably lead to similar considerations. We obtain the statistics by searching through the ACM Digital Library, IEEEXplore, and Elsevier’s Sciencedirect based on subject categories and relevant keywords. The complete list of articles used to obtain the statistics in Figure 1 is available at http://goo.gl/9Fzlve.

Table I. Structure of the Article

Subject	Topic	Section
Energy harvesting	Overview and desirable properties	2
	Kinetic sources	3
	Radiant sources	4
	Thermal sources	5
	Biochemical and chemical sources	6
	Discussion	7
Wireless energy transfer	Overview and desirable properties	8
	Mechanical waves	9
	Magnetic fields	10
	Electromagnetic radiations	11
	Discussion	12
Overarching considerations	Mapping WSN environments	13
	Research agenda	14

energy provisioning technology. We also intentionally only focus on solutions possibly applicable in low-power WSNs of resource-constrained devices, as they represent a significant domain with well-defined requirements. Energy harvesting and wireless transfer are applicable to other sensing platforms as well, such as personal mobile devices. These, however, exhibit different requirements compared to WSNs and would require a markedly different conceptual framework.

Notwithstanding the specific scope of our work, the subject matter is vast. As a result, the article is broadly structured in three parts, as illustrated in Table I:

(1) **Energy harvesting:** Section 2 introduces energy harvesting by explaining the fundamental distinction between energy source and corresponding extraction technique, by illustrating the desirable properties that harvesting solutions must present to be employed in WSN applications, and by introducing a classification of existing solutions to guide the reader. Sections 3 through 6 focus on the individual energy-harvesting solutions by illustrating the energy sources, their extraction techniques, and reported experiences of applying them to WSNs. Section 3 discusses kinetic energy sources, that is, the energy of motion, and ways to convert it into electrical energy. Section 4 illustrates radiant energy sources, which is the energy carried by electromagnetic radiations when they disperse. Energy sources due to thermodynamic gradients are described in Section 5, whereas Section 6 discusses the emerging forms of energy harvesting from biological or chemical sources. Section 7 wraps up the discussion by providing a summarizing view on the application of energy harvesting in WSNs; in particular, Table III compares the different solutions along the desirable properties previously illustrated.

(2) **Wireless energy transfer:** Section 8 introduces WET by eliciting the underlying relation to energy harvesting and by discussing desirable properties that WET techniques should present to be fruitfully employed in WSN applications. The individual WET techniques are illustrated in Sections 9 to 11 by focusing on the different transfer mechanisms and by reporting on real-world experiences. Section 9 illustrates the use of mechanical waves, and especially of acoustic ones, to transport energy through the oscillation of matter, that is, in the form of kinetic energy. Magnetic fields, which may serve for WET by means of inductive coupling or inductive resonant coupling, are discussed in Section 10. The use of electromagnetic waves such as visible light, microwaves, and RF transmissions to transfer energy over space is described in Section 11. Section 12 concludes the treatment

by offering a high-level view on the use of WET in WSN applications; in particular, Table V confronts different solutions along the properties introduced earlier.

(3) **Overarching considerations:** Section 13 maps existing energy-harvesting and wireless transfer solutions back to the characteristics of the target deployments, distilling a set of general guidelines to gauge the most appropriate technology. Section 14 describes open problems generated by the change of perspective brought by energy harvesting and wireless transfer, illustrating avenues for future research in areas as diverse as hardware design and environment models.

We end the article in Section 15 with brief concluding remarks.

2. ENERGY HARVESTING: OVERVIEW AND DESIRABLE PROPERTIES

Research in WSNs mainly concentrated on realizing advanced functionality within finite energy budgets, dictated by the battery capacities. Because of this, existing works mainly focus on finding optimal lifetime-performance tradeoffs at all layers of the stack. Harvesting energy from the ambient may potentially resolve this conflict, as already demonstrated in a number of concrete deployments [Sazonov et al. 2009; Vijayaraghavan and Rajamani 2010; Sardini and Serpelloni 2011].

To reason systematically on energy-harvesting solutions in WSN applications, we distinguish between the relevant *energy source* against the corresponding *extraction techniques*. The energy source indicates what environmental phenomena one may exploit to harvest energy. Examples are kinetic energy sources such as different forms of vibrations, and radiant energy sources such as solar or artificial light. Every source bears an intrinsic content of energy that may only partly be taken out, depending on the *extraction technique*. This is the specific technical solution to convert an environmental phenomena into electric energy. As a matter of fact, energy harvesting is indeed yet another form of energy conversion.

WSNs are a specific breed of networked system, with proper characteristics dictated by application requirements, hardware/software constraints, and deployment environments. When applied to WSN applications, energy-harvesting solutions should present a set of desirable properties, discussed next. These properties equally apply to a large set of deployment environments:

—**EH1: high energy density.** Sources should bear an intrinsically high energy content; because of the limited efficiency of current extraction techniques, harvesting is useful only whenever the energy density of the source can compensate it.

—**EH2: high efficiency.** To justify the added system complexity, a certain extraction technique should be able to take out the highest possible fraction of the energy density offered by a given source.

—**EH3: small form factor.** The extraction technique should operate at micro-level and the harvesting device be realizable in small form factors, ideally at most on the scale of the WSN node, not to complicate the deployments.

—**EH4: high robustness.** The harvesting equipment should be sufficiently reliable and require limited maintenance, even if exposed to stressful environmental phenomena; ideally, it should not further constrain the WSN lifetime.

—**EH5: low cost.** The harvesting equipment should be attainable at low cost, not to significantly impact the system's total cost of ownership.

Besides examining harvesting solutions based on these properties, we also consider off-the-shelf *availability* as an attribute of a particular extraction technique. This is relevant for determining whether the corresponding device can be seamlessly interfaced with a WSN device and readily employed. Differently, the design of custom integration hardware is often a function of whether an extraction technique is approximated by a

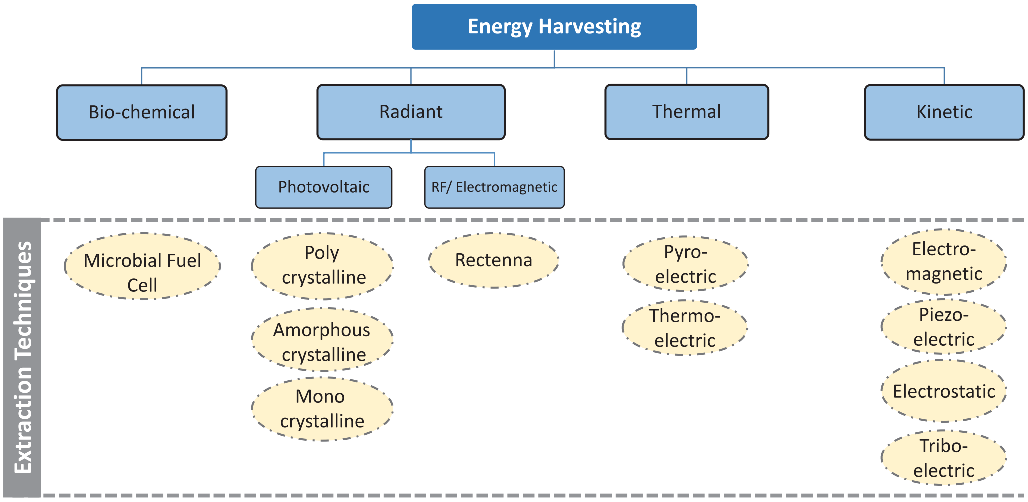


Fig. 2. Energy sources (rectangular blocks) and their extraction techniques (oval blocks).

voltage or a current source. The former type of source provides constant voltage as long as the current drawn from the source is within the source's capabilities and dually for the case of current sources. We analyze this aspect as well.

In the following sections, we study the nature of energy sources, their corresponding extraction techniques, along with relevant real-world WSN experiences. Our description is driven by the energy source, as it largely represents a determining factor for employing energy harvesting as a function of application requirements. Throughout the discussion, we cast the different solutions in the conceptual framework of Figure 2, which helps relate energy sources with the corresponding extraction techniques.

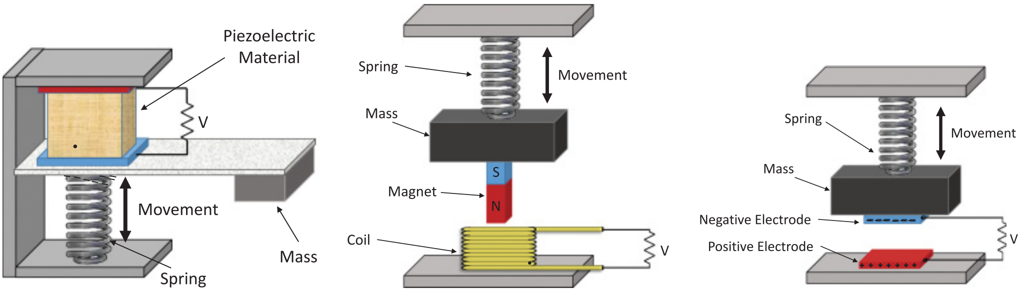
3. ENERGY HARVESTING → KINETIC SOURCES

Kinetic energy is the energy of motion, and one of the most fundamental forces of nature. It is formally defined as the work needed to accelerate a body of a given mass from rest to a certain speed. The body gains the energy during its acceleration and maintains this amount of energy unless its speed changes. The same amount of work is performed by the body when decelerating to a state of rest. Beyond the computing domain, leveraging kinetic energy to power various devices is an established practice. One example is that of self-winding watches, where the mainspring is wound automatically as a result of the natural motion of one's arm.

Kinetic energy may take numerous forms. In the following, we discuss popular forms of kinetic energy together with the corresponding, most commonly employed, extraction techniques. These, however, should not be intended as mutually exclusive categories. A given form of kinetic energy may, for example, easily transform into a different one. As a result, extraction techniques employed for one form of kinetic energy are sometimes applicable when kinetic energy manifests in different ways.

3.1. Kinetic Energy as Vibrations

Vibrations from manufacturing machines, mechanical stress, and sound waves are popular sources of kinetic energy. Vibration energy is typically of high density (**EH1**) and devices based on extraction techniques, discussed in this section, are readily available off-the-shelf at fairly low costs (**EH5**). Moreover, these extraction techniques enjoy



(a) Piezoelectric. (b) Electromagnetic. (c) Electrostatic.

Fig. 3. Simplified models of different vibration energy harvesters.

small form factors (**EH3**) together with useful harvesting efficiency (**EH2**). As a result, these solutions are extensively explored in the WSN literature, as shown in Figure 1.

Extraction techniques apt to these sources and applicable to WSNs are often based on *piezoelectric* [Mathna et al. 2008], *electromagnetic*, or *electrostatic* effects [de Queiroz 2013; Chye et al. 2010]. On a conceptual level, these solutions share the fundamental mechanism to convert vibrations into electric energy. Two sub-systems are involved: a *mass-spring* system and a *mechanical-to-electrical* converter. The mass-spring system transforms vibrations into motion between two elements relative to a single axis; the mechanical-to-electrical converter transforms the relative motion into electric energy by exploiting either of the three aforementioned effects.

Piezoelectric effect. Solutions exploiting this effect are based on a property of some crystals that generate an electric potential when they are twisted, distorted, or compressed [Poulin et al. 2004]. Whenever a piezoelectric material is put under some external force, it causes a deformation of the internal molecular structure that shifts positive and negative charge centers. This produces a macroscopic polarization of the material directly proportional to the applied force. The resulting potential difference across the material generates an alternating current (AC), which is then converted into direct current (DC); for example, using a full-bridge diode rectifier. Although a piezoelectric harvesting device naturally resembles a current source, it may also be leveraged as a voltage source [Kang 2012].

Although piezoelectric materials are not just used for harvesting energy from vibrations [Zhu et al. 2013; Paradiso and Feldmeier 2001], they are most often employed with a cantilever-like structure, shown in Figure 3(a). The cantilever acts as the mass-spring system. When the beam bends because of vibrations, it creates stress on the piezoelectric film, generating alternating current. The cantilever's resonant frequency is key in determining the efficiency and can be adjusted by changing the mass at the end of the beam and the material. Due to their mode of operation, these systems capture not only periodic ambient vibrations but also sudden or sporadic motion.

The choice of piezoelectric material greatly influences the harvesting efficiency (**EH2**). Several materials, both natural and artificial, exhibit a range of piezoelectric effects and are operational at the micro-level, thus also helping us to achieve small form factors (**EH3**). One of the most commonly used materials for piezoelectric energy harvesting is lead zirconate titanate (PZT), which is, however, brittle in nature and susceptible to cracks on high stress. This may negatively impact the device robustness (**EH4**). Another commonly used material is polyvinylidene fluoride (PVDF), which is comparatively more flexible than PZT. Although PZT and PVDF are capable of generating high voltage, the output current is low due to their high impedance, thus limiting the harvesting efficiency.

Electromagnetic and electrostatic effects. The electromagnetic effect is ruled by Faraday's and Lenz's laws, stating that a change in the magnetic conditions of a coils surroundings generates electromotive force. This causes voltage to be induced in the coil. To produce the change in the magnetic conditions around a coil, a magnet acts as the mass in a mass-spring system that produces movement parallel to the coils axis [Kulah and Najafi 2004; Mizunoand and Chetwynd 2003], as in Figure 3(b). This is not the only means to exploit the electromagnetic effect. For example, DeBruin et al. [2013] develop a current sensor that leverages the changes in the magnetic field induced by an AC current line. This, in turn, induces an AC signal on the secondary coil, producing sufficient energy to power the sensor device.

In the case of mass-spring systems, besides the magnet's mass, its material and the coils characteristics concur to determine the efficiency (**EH2**) of the harvesting device. Most solutions use neodymium iron boron (NdFeB) for the magnet, as it provides the highest magnetic field density (**EH1**). The number of turns and the material used for the coil help tune the resonant frequency according to the expected ambient vibrations. Although electromagnetic generators are more efficient than piezoelectric ones, their fabrication at the micro level is difficult: The assembly is complex and care must be taken to align the magnet with the coil. These aspects negatively impact robustness (**EH4**).

Differently, electrostatic transducers produce electric energy due to the relative motion of two capacitor plates, as in Figure 3(c). When the ambient vibrations act on a variable capacitance structure, its capacitance starts oscillating between its maximum and minimum values. An increase in the capacitance decreases voltage and vice versa. If the voltage is constrained, charges start flowing towards a storage device, converting the vibration energy into an electrical one. Consequently, electrostatic energy harvesters are modeled as current sources [Torres and Rincon-Mora 2006]. The main benefit of electrostatic transducers over piezoelectric and electromagnetic ones is the small form factor (**EH3**), as they can be easily fused into a micro-fabrication process [Roundy et al. 2003b]. However, they require an initial charge for the capacitor.

Reported experiences. Vibrations generated by vehicles are often used as sources of kinetic energy. For example, Sazonov et al. [2009] employ electromagnetic-based transducers to run a structural health monitoring (SHM) system for bridges, generating up to 12.5mW through vibrations due to vehicular traffic. Similarly, Vijayaraghavan and Rajamani [2010] implement a traffic-flow monitoring system through a self-sustained WSN that uses vibrations generated by passing vehicles.

Vibrations from vehicles may also power on-board sensors. Tolentino and Talampas [2012] design a self-powered vehicular tracking system that uses vehicle vibrations to generate energy through piezoelectric harvesters. Lohndorf et al. [2007] evaluate the possibility of a self-sustained tire pressure monitoring system by harvesting vibrations through electrostatic harvesters. To ensure the safety of industrial machinery in trailer trucks, Dondi et al. [2012] design a WSN of accelerometers and magnetometers using piezoelectric energy harvesters, powering the nodes from trailer-induced vibrations.

In other settings, Roundy et al. [2003b] experimentally verify that vibrations generated from a small microwave oven suffice to run a WSN node. They also empirically show that vibrations from various appliances, such as cloth dryers and blender casings, suffice to run small electronic equipment.

3.2. Kinetic Energy as Air or Water Flows

Wind mills and hydroelectric turbines are among the oldest known mechanisms to extract energy from air or water flows, respectively. Their operating principles are similar to those applied for vibrations. In most cases, some form of turbine converts a flow into

Fig. 4. Different forms of vertical air flow harvester.

a rotational movement. This movement subsequently drives an electromagnetic generator. These techniques are gaining popularity, as visible in Figure 1 from the recent increase of works about energy harvesting from air or water flows.

The physical characteristics of the turbine—specifically the number and type of blades and the axis of rotation—heavily influence the efficiency of the energy harvester. Whenever the air or fluid flows at high speeds, a few short and thin blades are more efficient, whereas at low speeds, numerous long, and wide blades achieve better efficiency. Generators with vertical axis rotation, as shown in Figure 4, are popular as harvesting devices, because they do not need to be pointed accurately in the direction of the flow, as opposed to horizontal-axis devices. These often employ a tail rotor to adjust their orientation along the direction of flow.

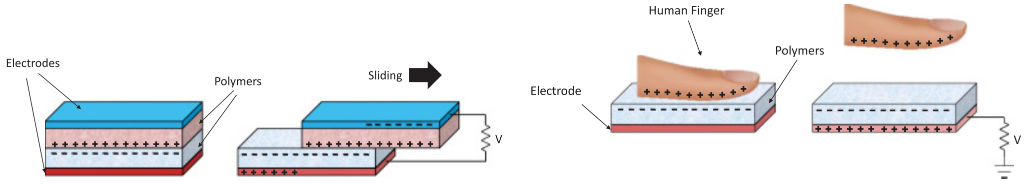
At micro-level, energy harvesters for air or water flows use miniaturized versions of traditional spinning turbines. In addition, the devices often take advantage of drag forces causing vibrations of the device itself, through an additional piezoelectric or electromagnetic harvester [Zhu et al. 2013]. Despite the wide variety of turbines available in the market, the large form factor (**EH3**) due to turbine components and the limited robustness (**EH4**) due to degradation that also induces high maintenance costs (**EH5**) limit their application to specific scenarios.

Reported experiences. Tan and Panda [2011] design a self-sustained forest fire monitoring system that uses micro wind turbines to harvest energy and to sense wind speed. To measure the latter, they use horizontal-axis turbines with a tail rotor for orienting the device along the direction of air flow. Similarly, Wu and Lee [2014] design a self-sustained forest fire monitoring system that solely runs on micro wind turbines but uses a temperature sensor to trigger the fire alarm. Sardini and Serpelloni [2011] design an energy harvesting wireless sensor to monitor temperature and air velocity in a building's air ducts. Sensed data are then used to automatically control Heating, ventilating, and air conditioning systems. In general, the use of air flows as sources of kinetic energy in indoor scenarios is increasingly popular [Park and Chou 2006; Xiang et al. 2013; Zhu et al. 2013].

Besides air flows, Chen et al. [2013] use a vertical-axis water turbine for powering WSN nodes in water pipes to monitor leakages and quality. Starner [1996] proposes the idea of energy harvesting from blood pressure, later realized by Deterre et al. [2014] by creating a self-sustained pacemaker. This device, even if not explicitly designed for networked sensing, demonstrates the feasibility of energy harvesting from flows at extremely small scales, which may be similarly applied in WSNs.

3.3. Kinetic Energy as Human or Animal Motion

As mentioned earlier, kinetic energy may easily transform from one form to another. This increases the general applicability of extraction techniques commonly employed



(a) Double electrode triboelectric harvester.

(b) Single electrode triboelectric harvester.

Fig. 5. Two modes of energy harvesting through the triboelectric effect.

for one form to a different form of kinetic energy. An illustrative example is that of kinetic energy from human motion. Extraction techniques employed for vibrations and described in Section 3.1—including those based on piezoelectric, electromagnetic, and electrostatic effects—are also applicable to harvest energy from human motion. For example, Paradiso and Feldmeier [2001] design a system able to harvest energy from the push of a button through a piezoelectric material. The device then transmits a digital identifier wirelessly, which can be used to control other electronic equipment.

In addition, it is possible to harvest electric energy from movements such as footfalls or fingers' motion through the *triboelectric* effect. This is one of the most natural phenomena, which occurs when different materials come into frictive contact with each other, becoming electrically charged. Rubbing glass with fur, or passing a comb through the hairs can, for example, yield triboelectricity. Various forms of energy harvesting using the *triboelectric* effect are possible. For example, Hou et al. [2013] show a triboelectric energy harvester embedded within a shoe able to power 30 light-emitting diodes. These devices are typically composed of two films of different polymers laid in a "sandwich" structure, as in Figure 5(a). The charge is generated by the rubbing of the two polymer films when they slide against each other and then captured by two electrodes.

To capture triboelectric energy generated by the touch of human skin, a single-electrode device is used, as in Figure 5(b). When a positively charged surface, such as a human finger, comes in contact with the polymer, it induces a negative charge on it. The overall circuit remains neutral as long as the two surfaces remain in contact, producing zero voltage on the load, as indicated on the left-hand side of Figure 5(b). However, as the positively charged surface moves away, as shown on the right-hand side of Figure 5(b), the polymer induces a positive charge on the electrode to compensate the overall charge. This makes the free electrons flow from the polymer towards the electrode and then to ground, producing output voltage on the load. Once the polymer comes back to the original state, the voltage drops back to zero.

The use of polymers in both these forms of triboelectric devices makes the structure flexible, improving robustness (**EH4**), and allows one to achieve small form factors (**EH3**). The latter feature, for example, facilitates the integration into wearable WSNs, where the skin rubbing against the harvesting device triggers the triboelectric effect. However, the scenarios where these technologies may be applied vastly differ, requiring significant customizations, as a solution is difficult to obtain of the shelf.

Reported experiences. Extracting energy from human motion is a natural choice in a number of scenarios, especially within the health-care domain. As an example, there exist implantable sensors able to harvest energy from muscular movements to transmit useful information about prosthetic implants [Silva et al. 2013; Almouahed et al. 2011]. Besides the aforementioned work by Paradiso and Feldmeier [2001], Frontoni et al. [2013] also use piezoelectric energy harvesters embedded within shoes to power active RFID tags for indoor localization. The range of application is not limited to scenarios

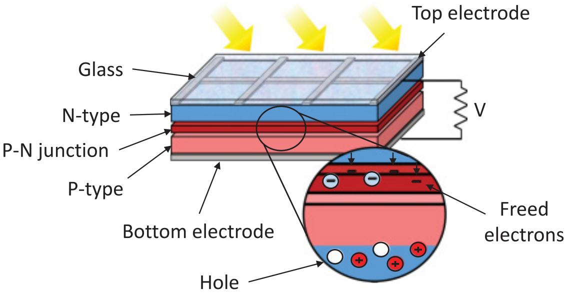


Fig. 6. Simplified model of a photovoltaic cell.

involving humans. Dopico et al. [2012], for example, demonstrate a herd localization system powered solely by harvesting energy from cattle movement.

4. ENERGY HARVESTING → RADIANT SOURCES

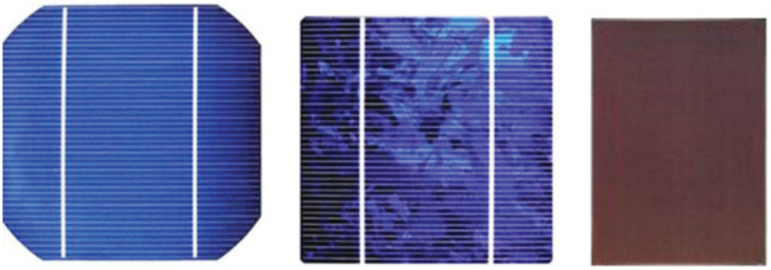
Radiant energy is the energy carried by electromagnetic radiations when they disperse from a source to the surrounding environment. The most common form of radiant energy is, of course, solar light. However, light radiation may or may not be visible. Besides light, a source of radiant energy that recently received increased attention are pre-existing RF transmissions.

4.1. Extracting Energy from Visible Light

The *photoelectric* effect allows one to extract energy from electromagnetic radiations below the infrared spectrum, with solar (visible) light as the primary example. Photovoltaic cells, leveraging the photoelectric effect, are one of the most mature energy-harvesting technologies. As Figure 6 depicts, a photovoltaic cell—also known as solar cell—consists of a minimum of two layers of semi-conducting material, mostly silicon. One of the layers, called the N-type layer, is doped with impurities to increase the concentrations of electrons. Likewise, freely moving positive charges called *holes* are introduced by doping the silicon of the other layer, thus called the P-type layer. Together, P-type and N-type layers form so-called P-N junctions.

When light hits the N-type layer, due to the photoelectric effect, the material absorbs the photons and thus releases the free electrons. The electrons travel through the P-N junction towards the P-type layer to fill the holes in the latter. Among the freed electrons, few of them do not find a hole in the P-type layer and move back to the N-type layer. This occurs through an external circuit, whereby the generated current is directly proportional to the intensity of light. Thus, photovoltaic cells are generally modeled as current sources [Kang 2012].

The material used in a cell's construction mainly determines its efficiency (**EH2**), along with form factor (**EH3**) and cost (**EH5**). Monocrystalline cells, shown in Figure 7(a), use a single crystal of silicon and are both most expensive and most efficient. However, they are not employed at the micro level because of their cost. Polycrystalline cells, shown in Figure 7(b), use multiple silicon crystals and can be recognized by their shattered-glass look. They are less efficient than monocrystalline cells, but their lower cost outweighs the efficiency losses. Amorphous silicon cells—also known as *thin-film* cells, shown in Figure 7(c)—are manufactured by depositing vaporized silicon on a substrate of glass or metal and may be flexible, which simplifies installation. These are both the least performing and cheaper type of cell; however, under typical indoor lighting conditions, they may outperform monocrystalline ones.



(a) Monocrystalline cell. (b) Polycrystalline cell. (c) Amorphous cell.

Fig. 7. Different types of solar cells.

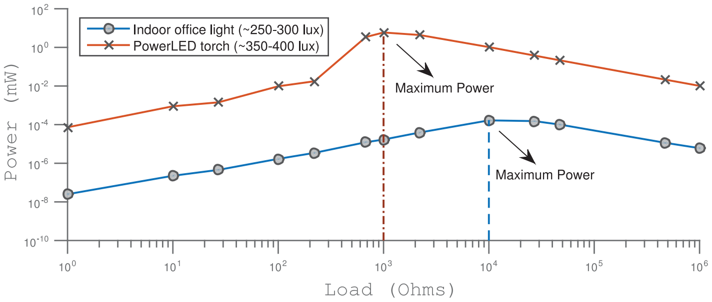


Fig. 8. Harvested power using amorphous silicon cells against different loads.

A characteristic of solar cells is the relation between their efficiency against the actual load and operating temperature. Figure 8 illustrates this relation for an amorphous cell. In conditions of office lighting, the cell gives maximum power with a load of 10,000Ω; when the same cell is under a PowerLED torch, it generates maximum power with a load of 1,000Ω. To leverage this phenomenon, solar cells usually incorporate a Maximum Power Point Tracking (MPPT) module, which tracks the output power and applies the appropriate load to optimize the output performance. In principle, MPPT modules may similarly assist the functioning of other energy-harvesting techniques [Yi et al. 2008], but their use is most commonly reported with solar cells.

Due to the high energy density of solar light (**EH1**) and off-the-shelf availability of existing solutions at relatively low cost (**EH5**), light-based energy harvesting is a popular means to power WSN nodes. The greatest advantage at the micro level is the lack of moving parts, which increases robustness (**EH4**), and the absence of emissions or noise. Nevertheless, the overall performance strongly depends on environmental conditions, that is, on light intensity and duration.

Reported experiences. Many cases of light-based energy harvesting can be found in the literature. For example, Gutierrez et al. [2014] design an automated irrigation system by extending the battery lifetime of WSN nodes using solar cells. A self-sustained transmit beacon is also reported [Roundy et al. 2003a], which uses both light and vibration energy harvesting to achieve up to 100% duty cycle.

The need to employ solar energy harvesting at the micro level also motivates novel solutions compared to the mainstream use of solar cells. For example, Brunelli et al. [2008] improve the efficiency of solar cells by designing a very low power (1mW) MPPT module for micro-level energy harvesting. Yerva et al. [2012] show a sensor device able to harvest sufficient indoor-solar energy to acquire and transmit sensor readings every minute along a collection routing tree. Differently, EnHANTs [Gorlatova et al. 2009] leverages solar radiations using organic semiconductors, enabling the use of bendable cells that facilitate deployments. The use of organic semiconductors allows the system to keep constant efficiency over different lighting levels, avoiding the need of MPPT modules. Finally, Prometheus [Jiang et al. 2005] and Everlast [Simjee and Chou 2006] use a super-capacitor as a primary buffer to store energy, the main advantage being a reduction of the recharge cycles of the main battery, which prolongs its lifetime.

4.2. Extracting Energy from RF Transmissions

Extracting energy from pre-existing RF transmissions recently received much attention, as shown in Figure 1, due to the increasing pervasiveness of cellular stations, FM radios, and WiFi networks.

The key element of an RF energy-harvesting device is the "rectenna," that is, a special type of antenna able to convert the energy carried by electromagnetic waves directly into electrical current. A rectenna comprises a standard antenna and a rectifying circuit. The antenna captures the electromagnetic waves in the form of AC current; the rectifier performs the AC-to-DC conversion, making a rectenna resemble a voltage-controlled current source [Nimo et al. 2015]. To design an efficient rectenna, different types of physical antennas, such as patch, dipole, planar, microstrip, and uniplanar antennas, may be incorporated with different types of rectifying circuits.

RF energy harvesting evidently bears a significant potential, yet it still requires evidence of practical applicability. Several efforts are undergoing towards this end; for example, studies exist to assess the feasibility of RF energy harvesting across different bands, such as those for digital TV, GSM900, GSM1800, 3G, and WiFi [Pinuela et al. 2013; Visser et al. 2008]. These works report power levels in harvested energy from nW to mW depending on the distance from the nearest base station.

The conversion of RF transmissions into electrical current through the rectenna does not involve any mechanical process as compared to other techniques and thus provides higher robustness (**EH4**). Small form factors (**EH3**) are attainable by employing specific types of antennas, such as micro-strip ones. In general, rectennas require highly customized solutions for a particular frequency band.

Reported experiences. RF energy harvesting is gaining momentum in a number of WSN applications. For example, several successful attempts exist in smart-health applications for powering wearable and implantable medical sensors from pre-existing RF transmissions. Cong et al. [2009] design a cubic millimeter-scale battery-less wireless sensor to monitor blood pressure powered by external RF sources. Similarly, Anacleto et al. [2012] build a cubic micrometer-scale rectenna able to harvest 1μW, which can be used to power wireless implantable sensors.

Prototypes of RF-harvesting wireless sensors for HVAC control and building automation are also reported [Olgun et al. 2012; Kurilj et al. 2014]. These harvest energy from the unlicensed 2.4GHz Industrial, scientific, and medical band, that is, the one used by WiFi, Bluetooth, and other commodity wireless devices. Being one of the most crowded portions of the spectrum, harvesting energy from these frequencies is typically very effective. General-purpose WSN platforms harvesting RF energy also exist [Parks et al. 2013; Nishimoto et al. 2010]. These provide a stepping stone to validate the practical applicability of the related harvesting techniques.

Worth noticing is that the use of RF energy harvesting goes beyond merely powering WSN devices. For example, Liu et al. [2013b] combine RF energy harvesting with backscatter communications and create a communication primitive where devices communicate by backscattering ambient RF signals. This eliminates the need for both dedicated power sources and wires for communication.

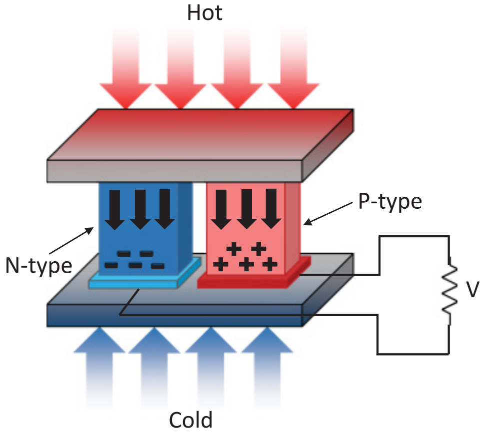


Fig. 9. Simplified illustration of thermoelectric effect leading to electrical current.

5. ENERGY HARVESTING → THERMAL SOURCES

Thermal energy refers to the internal energy of an object in conditions of thermodynamic equilibrium, that is, in the absence of macroscopic flows of matter or energy, and in conditions of constant temperature. Whenever the conditions of thermodynamic equilibrium cease to exist, the resulting matter or energy flows become usable to harvest electric energy through *thermoelectric* or *pyroelectric* techniques.

Thermoelectric techniques are based on Seebeck's effect, which is conceptually similar to the photovoltaic techniques in Section 4.1. N-type and P-type materials are employed here as well, as shown in Figure 9. As the temperature difference between opposite segments of the materials increases, charges are driven towards the cold end. This creates a voltage difference across the base electrodes, which is proportional to the temperature difference. Thus, thermoelectric harvesters can be modeled as voltage sources [Kang 2012]. Silicon wafer or aluminum oxide are typically used as a substrate material, because of their large thermal conductivity.

In contrast, pyroelectric energy harvesters leverage materials with the ability to generate a temporary voltage as their temperature is made continuously varying, much like piezoelectric materials generate a potential when they are distorted, as discussed in Section 3.1. Specifically, the temperature changes cause the atoms to re-position themselves in a crystalline structure, changing the polarization of the material. This induces a voltage difference across the crystal, which gradually disappears due to leakage currents if the temperature stays constant.

Generally, the extraction techniques operating from thermal sources have no moving parts and are therefore more robust (**EH4**) to environment factors compared to other micro-level harvesters. The devices may thus achieve operational lifetimes of several years without maintenance. Because of their mode of operation, it is also relatively simple to achieve small form factors (**EH3**). Both thermoelectric- and pyroelectric-based harvesters are becoming increasingly available off the shelf.

Reported experiences. Several works exist reporting on the use of energy harvesting from thermal sources to power WSN devices. For example, Zhao et al. [2014] design a self-powered WSN node that harvests energy from temperature fluctuations in the environment. Similarly, structural health monitoring systems for oil, gas, and water pipes [Martin et al. 2012; Zhang et al. 2011] leverage thermal sources such as hot water and steam. Rizzon et al. [2013] use heat dissipated from CPUs in data centers to run a WSNs for environment monitoring. Energy harvesters based on thermal

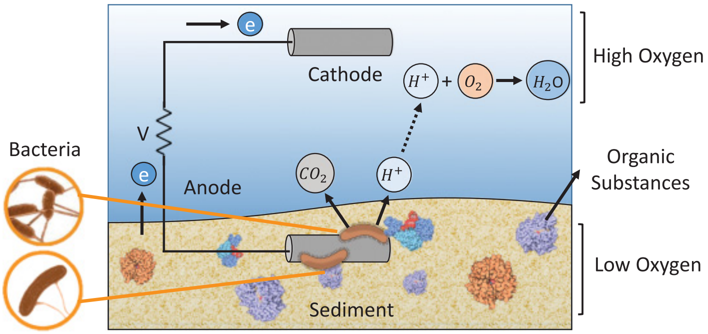


Fig. 10. Working of a microbial fuel cell: as part of their natural nutrition processing, bacteria remove electrons from organic material; these flow through an anode-cathode, battery-like, structure where the two compartments are separated in terms of their O_2 concentration.

phenomena may operate both as sensors and energy harvesters [Campbell et al. 2014]; for example, by measuring temperature differences in the environment as a function of the produced energy. Also, the warmth of humans or animals may be used to power medical sensors [Lossec et al. 2013], even though the applications in these areas do not appear to leverage networking functionality.

6. ENERGY HARVESTING → BIOCHEMICAL AND CHEMICAL SOURCES

Energy harvesting may leverage forms of *biological* or *chemical* energy in specific environments. Biochemical energy is the potential of a chemical substance to produce electrical energy through a chemical reaction or through the transformation of other chemical substances. Humans embody the biochemical harvesting pathway, as we power ourselves by the conversion of food into energy through biochemical processes. Differently, the electric battery is an example that uses chemical processes to convert naturally occurring chemical reactions into electricity [Qiao et al. 2011].

Among biochemical extraction techniques, microbial fuel cells (MFC) use biological waste to generate electrical energy, as schematically shown in Figure 10. Bacteria in water metabolize biological waste by breaking it down in a process of oxidization. This results in the creation of free electrons, along with CO_2 and H^+ ions. If the environment is deficient in oxygen, then an anode picks up the free electrons and transports them to a corresponding cathode where, in an environment abundant in oxygen, the reduction process completes, yielding a water molecule.

The efficiency of an MFC is thus a function of the difference in oxygen concentration across the anode and the cathode sections. This is why, for example, MFCs deployed in marine environments have the anode partly embedded in soil and the cathode placed close to the surface, at a higher oxygen concentration, as in Figure 10. MFCs are thus modeled as a voltage source in series with a resistance. As energy-harvesting devices, MFCs are usually robust (**EH4**) and require little maintenance, as long as the renewable resource, such as biological waste, is available. Recent results also indicate the potential to harvest energy from voltage differences across the xylem of a tree bark and the soil [Love et al. 2008], using similar principles.

MFCs are usually employed to power medium-to-large scale electronic devices. For miniaturized devices, such as biomedical implants, enzymatic biofuel cells are also considered [MacVittie et al. 2013]. Enzymes are proteins generated by living organisms to catalyze chemical reactions. Unlike MFCs, enzymatic biofuel cells do not use living organisms to trigger the oxidation process but only some of the enzymes that specific microorganisms produce, which are carefully extracted and purified for use. This results in higher energy efficiency (**EH2**) than MFCs, at the expense of higher production costs (**EH5**) [Armstrong 2010]. Moreover, the power densities of enzymatic biofuel cells vary significantly compared to MFCs, as they are typically several times smaller [Calabrese Barton et al. 2004].

Extraction techniques based on chemical processes typically focus on taking advantage of corrosion phenomena; for example, those occurring on steel bars used to reinforce concrete structures. The two main factors responsible for the corrosion of steel in cement are carbonation and oxidation under the presence of water that seeps through cement pores. These elements, when reacting with iron (Fe), form new compounds like hydrated iron oxides ($Fe_2O_3nH_2O$) or iron oxide-hydroxide (FeO(OH), also known as rust), while releasing electrons. The portion of the steel that releases electrons acts as anode, whereas the portion of metal that accepts the electrons acts as cathode, with water acting as an electrolyte. The resulting flow of electrons is harvested in the form of electrical current.

Reported experiences. Several WSN applications exist where the sensed phenomena is a naturally occurring biochemical or chemical process. Reimers et al. [2001] establish the viability of powering small oceanographic sensors by demonstrating a constant output power of 0.05W/m^2 from MFCs in a marine settings. Donovan et al. [2008] design a power management system to boost the voltage of MFCs for powering wireless temperature sensors over a period of 1 year in natural water. Gong et al. [2011] use a tiny 0.25-m footprint MFC with average output power of 44mW/m^2 to power an acoustic modem for transmitting temperature measures over 50 days. Similarly, Kaku et al. [2008] and Dai et al. [2015] place MFCs in rice paddies and forests to power wireless sensors. Building on the work by Love et al. [2008], Voltree Inc. devises a custom sensor platform that harvests energy from voltage differences across tree barks and soil, demonstrating a large-scale forest fire detection system [Voltree 2009; Karavas et al. 2007].

As for chemical processes, corrosion phenomena often present an opportunity for in situ sensing. Qiao et al. [2011] design a steel corrosion monitoring system for reinforcing concrete structures where they harvest the needed energy from the corrosion process. Similar cases are reported in the design of sensing systems for waste water treatment [Mohan et al. 2008; Ewing et al. 2014]. Several results indicate that the corrosion process can produce energy in the range of a few mW over a period of several hours, which is sufficient to power small electronics [Qiao et al. 2014; Ouellette and Todd 2014; Sun et al. 2013].

7. ENERGY HARVESTING: DISCUSSION

Table II illustrates a summary view on the use of energy harvesting in WSN applications, based on a set of representative examples. Key observations we draw are as follows:

—Energy harvesting from kinetic sources is vastly employed in WSN applications. The harvesting performance varies greatly, from few μW to tens of mW, as it depends on ambient characteristics and efficiency (**EH2**) of the specific technique. In many cases, the harvested energy suffices to run mainstream WSN platforms, such as the TelosB node that requires less than 10 mW to achieve 10% duty cycle [Bhatti et al. 2014]. In several applications, the ambient can supply energy in a *continuous* manner. In these cases, harvesting techniques for kinetic sources also enable continuous operation of the WSN nodes, that is, whenever ambient energy is available, the system can run using only tiny energy buffers, helping to cut down costs (**EH5**). This is contrast to the larger energy buffers, or supplementary batteries, employed whenever the ambient energy is insufficient to fully sustain the system's operation.

Table II. Representative WSN Deployments Employing Energy Harvesting and Their Key Characteristics

Energy source		**Extraction technique**	**Application**	**Harvested power**	**Energy availability**	**Operation**	**Literature reference**
Kinetic	Vibration	Electromagnetic	Structural health monitoring	12mW	Intermittent	Intermittent	Sazonov et al. [2009]
	Vibration	Piezoelectric	Safety of vehicles	13.5uW	Continuous	Continuous	Lohndorf et al. [2007]
	Vibration	Piezoelectric	Safety of agriculture machinery	724uW	Intermittent	Intermittent	Scorcioni et al. [2011]
	Air flow	Electromagnetic	Detection of forest fire	7.7mW (@ 3.6m/s)	Continuous	Continuous	Tan and Panda [2011]
	Air flow	Electromagnetic	Automatic HVAC	45mW (@ 9m/s)	Intermittent	Intermittent	Sardini and Serpelloni [2011]
	Water flow	Electromagnetic	Water pipe monitoring	18mW	Continuous	Continuous	Morais et al. [2008]
	Human motion	Piezoelectric	Biomedical implants	1mW	Intermittent	Intermittent	Almouahed et al. [2011]
	Animal motion	Electromagnetic	Herd localization	N/A	Intermittent	Intermittent	Dopico et al. [2012]
Radiant	Indoor light	Amorphous crystalline	Indoor applications	180uW	Intermittent	Intermittent	Roundy et al. [2003a]
	Sun light	Amorphous crystalline	Smart irrigation	240mW	Intermittent	Continuous	Gutierrez et al. [2014]
	Ambient RF	Rectenna	Outdoor sensing	60uW	Continuous	Continuous	Sample et al. [2007]
Thermal		Thermoelectric	Environment monitoring	218uW	Continuous	Continuous	Rizzon et al. [2013]
		Thermoelectric	Water metering	250uW	Continuous	Continuous	Campbell et al. [2014]
Bio-Chemical		Microbial fuel cell	Precision agriculture	310.24uW	Continuous	Continuous	Pietrelli et al. [2014]

Table III. Energy Harvesting Solutions Against the Desirable Properties of Section 2. The Power Density Ranges Are Taken from the Papers Referenced in Table II. Conversion Efficiency Data, Whenever Available, Are Taken from Vullers et al. [2009] and Sudevalayam and Kulkarni [2011]

	Type of energy harvesting						
Property	**Biochemical**	**Visible light**	**RF transmissions**	**Thermal**	**Vibrations**	**Air/water flows**	**Human/animal motion**
Power density	Low (~300μW)	Low (180μW) to high (240mW)	Low (~100μW)	Low (218μW to 250μW)	Low (700μW) to medium (12mW)	Medium (7.7mW to 18mW)	Medium (~1mW)
Conversion efficiency	N/A	~0.1% to 15%	~33%	~0.1% to 10%	N/A	N/A	~7.5% to 11%
Form factor	Large	Small	Medium	Small	Small	Large	Small
Robustness	High	High	High	High	Low	Low	Low
Cost	Medium	Low	Medium	Low	Low	High	Low

—Radiant sources are also popular in WSN applications; for example, when relying on solar light. The harvesting performance is in the mW range for visible light but lowers by several orders of magnitude when harvesting from RF transmissions. This limits the application of the latter to extremely low-power settings. In both cases, the performance is strongly influenced by the size of the harvesting device, a solar cell or a rectenna, and by the distance from the source.

The behavior of radiant sources is also more predictable as compared to others; sunlight can be forecast and RF transmissions are almost omnipresent nowadays. These aspects facilitate achieving perpetual operation using these harvesting techniques. Even when ambient energy is not continuously available, the intermittent supply of energy from solar light can be counteracted by equipping the nodes with suitably dimensioned energy buffers [Gutierrez et al. 2014] or by adapting the duty cycle depending on the expected energy availability [Buchli et al. 2014].

—The remaining cases of thermal and biochemical sources, besides being among the most natural forms of harvestable energy, are also those with the lowest reported performance in WSN applications, typically in the μW range. This might be sufficient to power individual sensors performing local data processing but not for achieving full-fledged networking functionality. Nevertheless, compared to kinetic and radiant sources, thermal and biochemical sources exhibit unique characteristics. Energy from the ambient is continuously available, and the harvesting performance is sufficient to let the system run continuously. Extraction techniques from thermal sources also enjoy high robustness (**EH4**) because of the lack of moving parts, whereas MFCs can power WSN applications in environments where no other energy source is at disposal, as in underwater scenarios.

Table III wraps up our discussion on energy harvesting by qualitatively indicating to what extent different harvesting techniques meet the desirable properties of Section 2, independent of their reported use in WSN applications. With this, we intend to foster new directions besides the trends already apparent in the literature. We can draw the following observations from the analysis:

Fig. 11. WSN deployment on the Matterhorn cliffs: node C faces northwest and is rarely exposed to the sun.

- Highest energy density (**EH1**) is found in visible light and human motion. Their extraction techniques; for example, based on photoelectric and triboelectric effects, enjoy high efficiency (**EH2**) and low cost (**EH5**). As in all other kinetic sources, however, the latter has moving parts, which is detrimental to robustness (**EH4**).
- Extraction techniques from thermal sources and mechanical vibrations exhibit the smallest form factors (**EH3**) among available solutions. In the latter case, the process of miniaturization tends to negatively affect robustness (**EH4**).
- More than a single technique is available at a reasonable cost (**EH5**) compared to mainstream WSN technology, with the only exception being harvesting devices from air/water flows, which tend to be expensive.

The next section focuses on WET, its relation to energy harvesting, and its use in WSN applications.

8. WIRELESS ENERGY TRANSFER: OVERVIEW AND DESIRABLE PROPERTIES

Energy harvesting is attractive to prolong the WSN lifetime and to possibly enable perpetual operation. However, harvesting is only possible if the system is deployed where a sufficiently high-density energy source is available. In some deployments, this is simply not the case. In other settings, the availability of energy sources may be inconsistent across the deployment area, creating an energy imbalance.

Figure 11 shows a real-world example of the latter situation, taken from the WSN deployment at the Matterhorn mountain complex [Hasler et al. 2008]. Node C, installed on the northwest side of the mountain, is not exposed to sunlight as often as nodes A and B. Applying energy harvesting from light is thus most effective only for nodes A and B, whereas node C would constantly enjoy a smaller energy contribution from the harvesting device.

Recent advancements in WET, that is, the ability to wirelessly move energy in space, can decouple the sensing location from where energy harvesting is most efficiently applied. For example, WET can transport harvested energy to locations where ambient energy is scarce, as in the case of Figure 11. Moreover, WET can balance energy provisioning within a WSN characterized by non-uniform workloads, taking from energy-rich nodes and giving to energy-poor ones. Without applying WET, these situations may result in a non-functional system even when the globally available energy would be sufficient.

Most WET techniques include two components: (i) a *transfer mechanism*, that is, the technical solution that allows the system to move energy across space wirelessly,

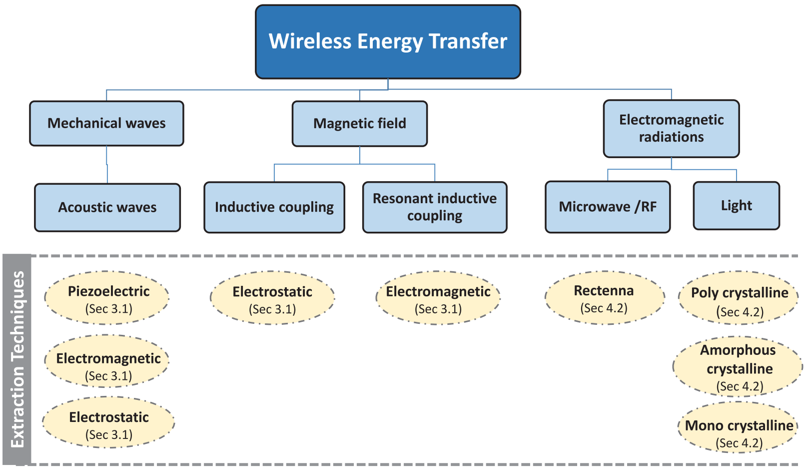


Fig. 12. Existing transfer mechanisms and corresponding harvesting techniques.

and (ii) a corresponding *harvesting technique* used at the destination to gain back the energy. Therefore, energy harvesting is one, but not the only, functional component of WET. In principle, applying WET to a certain location is analogous to *artificially provisioning* an environment with *harvestable ambient energy* at that location.

Figure 12 shows the relation between transfer mechanism and harvesting technique and may be taken as a reference throughout the coming material. The harvesting techniques are largely the same as those discussed earlier. In the following section, we therefore concentrate on the other functional component of WET, that is, on the transfer mechanism. Separating the treatment of energy harvesting and transfer mechanisms is instrumental to elicit the complementary aspects between the two.

Similarly to Section 2, we identify the desirable properties that WET techniques should present. These are intended in addition to those already discussed for energy harvesting, in that the individual WET techniques necessarily include a harvesting component. Some properties might not be as relevant for WET as for energy harvesting. For example, compared to the cost (**EH5**) and availability of different harvesting solutions, wireless energy transmitters such as antennas, torches, and lasers are known to be commercially available at fairly low prices. Differing from Section 2, the following properties may take *strikingly different* forms depending on the target deployment scenario:

—**WET1: high efficiency.** To be effective, a given WET technique should maintain the highest possible ratio between the energy harvested at the receiver and the one emitted by the source.

—**WET2: small form factor.** The harvesting part should operate at a micro level; the same requirement is less stringent for the transmitter part, in that the energy source is not necessarily integrated with a WSN node.

—**WET3: long range.** The operational distance of WET without considerable losses should minimally impact the deployment configuration, most often dictated by application or networking requirements.

—**WET4: high permeability.** It defines the ability to travel through obstacles of different types; certain technologies can easily traverse certain materials, such as air or water but need line of sight or exhibit drastic losses w.r.t. other materials.

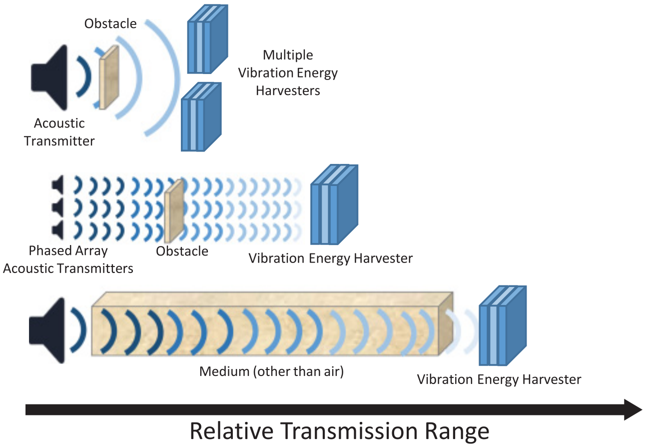


Fig. 13. Acoustic waves are compressional; therefore, the efficiency, range, and permeability depend on the medium of propagation. Given a specific medium, better performance is attainable by employing multiple harvesting devices at the receiver's end or by using phased arrays of transmitters.

—**WET5: safety.** WET is about spreading energy in the ambient; the possibility of harming objects or persons is thus a concern, and care must be taken to determine whether a certain technique may be unsafe within its operational range.

—**WET6: routability.** It indicates technologies known to feature efficient ways to route energy across multiple hops; whereas simply harvesting received energy and using this to act as a further source is likely too inefficient.

An additional aspect is that of directionality. Existing solutions may operate in a directional fashion—with greater efficiency and range—as opposed to an omni-directional mode, which facilitates deployments by removing the need to orient the transmitters.

Next, we survey WET techniques that find application in WSNs. The discussion is driven by the transfer mechanism, as it largely determines the applicability in WSNs. The illustrative pictures shown in the next sections are *to scale* compared to each other, which enables a qualitative comparison of operational ranges.

9. WIRELESS ENERGY TRANSFER → MECHANICAL WAVES

Mechanical waves propagate as an oscillation of matter. Such oscillation transfers kinetic energy through a medium, such as air or water. Of the existing forms of mechanical waves, acoustic waves, that is, waves that propagate because of displacement and pressure changes of the medium, are by far the most explored for WET. Acoustic waves cause a vibrational movement onto the receiving elements. This enables the use of vibrational harvesting, discussed in Section 3.1, to gain back the energy. Other kinds of mechanical waves that require more sophisticated harvesting mechanisms, such as surface waves, are comparatively less explored. This represents, in fact, a consequence of the complementary aspects between the transfer mechanism used in WET and the corresponding energy-harvesting technique.

As shown in Figure 13, acoustic waves are compressional, that is, the displacement of the medium is parallel to the direction of travel of the wave. Thus, their efficiency (**WET1**), range (**WET3**), and permeability (**WET4**) are greatly affected by the medium itself. Acoustic waves travel best through solids, then liquids, and show the most resistance through air. For example, acoustic waves are shown to transfer energy through metal walls 5cm to 8cm thick with efficiency of 50% to 89% [Bao et al. 2008; Shoudy et al. 2007]. The efficiency in water varies from 15% to 40%; for example, Ozeri et al.

[2010] achieve 39% efficiency in water at a distance of 50mm. Whenever waves travel through air, the efficiency drops to 17% at a 100mm distance [Roes et al. 2011]. We also observe ultrasound-based solutions [uBeam 2015] appearing on the market to charge personal devices through the air.

The propagation medium, however, is often not under the control of the WSN designers. To improve the performance in given settings, multiple vibration harvesters may be installed at the receiver's end, or transmitters may be arranged in a phased array configuration, which helps travel though objects, as shown in Figure 13. Acoustic waves also enjoy slower propagation speed than other kinds of waves, such as electromagnetic ones. This makes it possible to achieve more compact designs of the transmitters as well as greater efficiency (**WET1**) for the transmission electronics at the operational frequencies [Roes et al. 2013]. Finally, in settings where the transmission medium is animal tissue or human skin, acoustic waves naturally provide better safety (**WET5**) than other techniques, such as lasers.

Reported experiences. A paradigmatic example is that of body sensor networks [Charthad et al. 2014; Arra et al. 2007], where safety becomes a key asset for cm- to mm-sized bioimplants. In settings where WET using electromagnetic waves is not possible or permissible, acoustic waves are often used. Examples are deployments where acoustic waves are used to power sensors embedded in metals walls, water pipelines, and gas chambers [Kluge et al. 2008; Shoudy et al. 2007; Graham et al. 2011; Hu et al. 2008]. Because of their permeability (**WET4**) properties, acoustic waves are also employed to power electronic equipment in sealed environments, such as nuclear storage facilities, where the sensors leverage piezoelectric extraction techniques to harvest the energy [Hu et al. 2003].

10. WIRELESS ENERGY TRANSFER → MAGNETIC FIELDS

WET techniques using magnetic fields mainly leverage energy harvesting based on electromagnetic effects. In Section 7, we already noted how the latter are vastly employed in WSN applications and enjoy good properties. Coupled with this kind of energy harvesting, two transfer mechanisms are primarily used: inductive coupling and resonant inductive coupling.

Inductive coupling is a near field—in the cm scale—WET technology that exploits two magnetically coupled coils. When alternate current is applied to the transmitter coil, this changes the magnetic field of the receiver coil, generating a potential. The mechanism is similar to the electromagnetic extraction mechanisms of Section 3.1, except here we use a coil instead of a magnet to disturb the magnetic field. The efficiency (**WET1**) of such a system is determined by the coupling of the coils, their distance, and their alignment. Over longer distances, the vast majority of the energy is lost because of resistive losses of the transmitter coil. This technique is thus solely suitable for WSN applications where the necessary operational range (**WET3**) is not significant.

Inductive resonant coupling, on the other hand, adds a capacitance to each coil, thus forming a tuned LC circuit, as shown in Figure 14. When both coils resonate at a common frequency, it is possible to attain high efficiency (**WET1**) over a range a few times greater than the coil's diameter. Kurs et al. [2007] demonstrate this effect by powering a 60W light bulb with approximately 40% efficiency over a 2m distance. Recent results also make this technique more flexible in terms of reciprocal orientation of the coils. For example, Sample et al. [2011a] use adaptive tuning techniques to transfer energy at 2m with high efficiency, even when coils are not properly aligned. The same system is used to run an artificial heart [Waters et al. 2014]. Sample et al. [2011b] show that a constant efficiency of 75% is attainable within a 65° coil rotation angle, using continuous frequency tracking and tuning of the resonant coil structure.

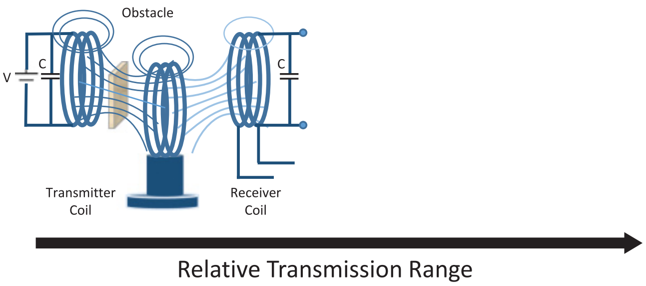


Fig. 14. Inductive resonant coupling allows medium-range energy transfers at high efficiency, and adding relay coils can further extend the range.

Inductive resonant coupling also caters for non-radiative transmission of energy, which entails the propagation of energy is not subject to phenomena such as absorption and scattering. To this end, the magnetic field is created all around the transmitter coil, with the orientation of the receiver coil impacting the efficiency. Being non-radiative, inductive resonant coupling dissipates little energy off to resonant objects [Kurs et al. 2007], preventing spreading losses typical of acoustic waves. This techniques is also permeable (**WET4**) through metals and tissues and remains safe (**WET5**) if low levels—in the range of mW to a few W—of power is transferred. Zhong et al. [2013] show inductive resonant coupling to support routing (**WET6**) using straight-line, curved, circular, and Y-shaped intermediate coils, as in Figure 14. Several commercial solutions based on resonant inductive coupling appeared [WiTriCity 2015; Qualcomm 2015; PowerByProxi 2015], improving off-the-shelf availability of this technology.

Reported experiences. As already mentioned, WET using inductive coupling is applicable only at very short ranges, and thus we only find experiences of resonant inductive coupling in WSNs. Nonetheless, the use of the latter technique in WSNs is arguably in its infancy, so not many works exist that report such experiences.

For example, Jonah and Georgakopoulos [2011] use resonant inductive coupling to power sensors embedded in concrete at a 40cm depth with 5.3% efficiency. Xie et al. [2012] design a WSN powered with resonant inductive coupling through a wireless charging vehicle, aiming at the optimization of the traveling path and charging times. Hancke and Vorster [2014] demonstrate powering a MicaZ node with just a 3.2cm diameter coil, at 10% duty cycle and a distance of 80cm. Finally, Sample et al. [2011a] use resonant inductive coupling to power an underwater WSN at a depth of 1,000m.

11. WIRELESS ENERGY TRANSFER → ELECTROMAGNETIC RADIATIONS

Electromagnetic radiations are a form of radiant energy released by a certain electromagnetic process. Visible light is a common type of electromagnetic radiation; other forms are instead invisible to the human eye, such as X-rays and radio waves.

Electromagnetic radiations are distinguished based on their frequency. Such a distinction also affects the techniques to gain back the energy the radiation carries, further underlining the complementary aspects of the transfer mechanism and of the corresponding energy-harvesting technique. Electromagnetic radiations below the infrared spectrum—mainly visible light—pack sufficient photonic energy to use extraction techniques based on the photoelectric effect, illustrated in Section 4.1. We already noted, as reported in Section 7, how such techniques are among the most mature means for energy harvesting. Electromagnetic radiations at higher frequencies, such as

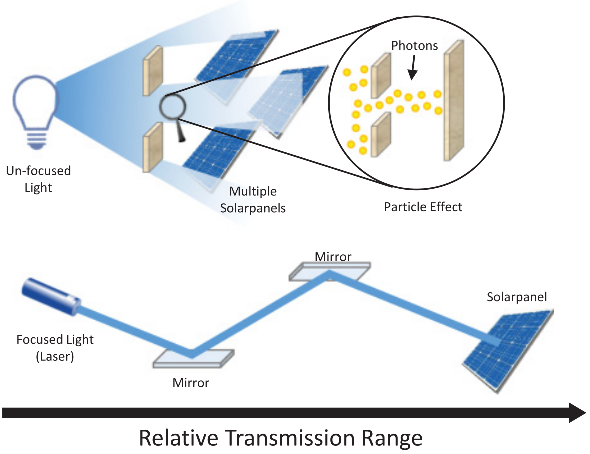


Fig. 15. WET using visible light. Incoherent sources suffer spreading and frequency losses but also ameliorate the alignment requirements. Focused sources, such as lasers, require careful alignment but also allow for greater efficiency and range.

microwaves and RF transmissions,[2] require the use of rectennas, discussed in Section 4.2. Still, based on the discussion in Section 7, these are comparatively less developed than energy harvesting using the photoelectric effect.

11.1. Visible Light

It is possible to artificially generate visible light radiations and direct them towards a photovoltaic surface to enable energy transfer at a distance. Within the visible spectrum, there exist two means to transfer energy, as shown in Figure 15.

One possibility is to use the light diffused from sources such as incandescent bulbs or LEDs. This type of radiation tends to be incoherent and unfocused, thus creating spreading losses due to the light beam diverging as it travels across space. The produced light also consists of several different frequencies, thus spreading the energy across the frequency domain. Thus, this approach tends to be applicable only in the short range, due to quadratic-to-distance spreading losses and because the receiving cells often tend to be efficient only for a subset of the involved frequencies. As an example, Bhatti et al. [2014] show that a 1W LED can transfer a few mW but only at very short distances.

Laser light is, on the other hand, a stimulated emission of photons that results in a coherent and focused beam of light energy. These characteristics allow a laser beam to bear minimal losses due to spreading across space, enabling efficient energy transfer at very long ranges (**WET3**), even hundreds of Km. Since the emitted light is limited to a narrow band of frequencies, the efficiency mainly rests on the choice of the correct photovoltaic material corresponding to the used frequency bands.

Both forms of light radiation can be artificially generated from a power source or obtained from sunlight. For example, Syed et al. [2010] use mirrors to route (**WET6**) sunlight to locations under shade, where energy harvesting using photovoltaic techniques occurs. Sunlight can be used as the lasing source in solar-pumped lasers, sparing an artificial power source [Liang and Almeida 2011]. Visible light, being not permeable to most materials, requires a clear line of sight. Moreover, while normal light is

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[2] Microwaves represent the 300MHz-to-300GHz band of the electromagnetic spectrum, while RF transmissions represents the 3MHz-to-300MHz band.

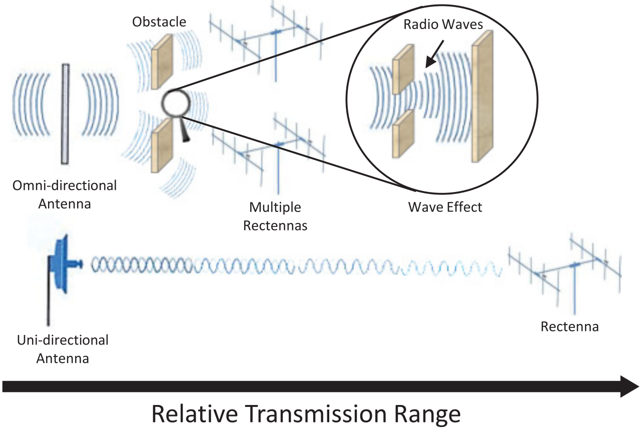

Fig. 16. WET using microwaves and RF transmissions. Large antennas are typically required, hampering their application to WSN-size devices. Omni-directional antennas pose less stringent line-of-sight requirements but are less efficient because of spreading losses.

generally safe (**WET5**), laser light may pose safety hazards, even at low-power rating, due to its focused nature that results in higher energy density.

Reported experiences. Visible light is vastly explored as a WET technique to power WSN nodes. For example, reflection systems exist that use mirrors to balance the spread of sunlight in solar-harvesting sensor networks [Liu et al. 2013a; Syed et al. 2010]. LAMP [Bhatti et al. 2014] shows a practical laser-based long-range solution for WSNs and develops a system architecture able to power a TelosB node with 10% duty cycle at a distance of 100m using a 0.8W laser. Wang et al. [2012] use laser light to simultaneously power multiple nodes by diffusing the light through phosphorus surfaces, eliminating the need to accurately localize the receiver nodes. Using a 3W laser source, they are able to harvest 85μW at a distance of 1.5m.

11.2. Microwaves or RF Transmissions

Electromagnetic radiations at frequencies higher than visible light carry energy that can be gained back using a rectenna, described in Section 4.2. This kind of WET is extensively studied for long-distance energy transfers—in the order of several Km—and for high-power systems. The existing literature reports the use of these techniques to power airplanes [Schlesak et al. 1988], helicopters [Brown 1969], and even satellites [Matsumoto 2002]. These techniques, however, also require line of sight because of the low permeability, as well as a tracking mechanism to localize the receiver, due to directional energy transfer towards a moving target.

As shown in Figure 16, using an omni-directional antenna, such requirements become less stringent than for laser power beaming and the transfer mechanism is safer (**WET5**), at the cost of higher spreading losses similar to unfocused sources of visible light. Ensuring safe operation of these systems is an actively researched topic. For example, algorithms exist to interrupt transmitters to avert dangerous continuous radiations [Dai et al. 2014a] or to adjust their transmission power [Dai et al. 2014b] to avoid safety hazards while retaining an efficient energy transfer.

Because of longer wavelengths, a large antenna is also normally required at both the source's and the receiver's end, in principle hampering the application to WSNs because of large form factors. Several studies to miniaturize the rectenna design have been published [Soltanzadeh et al. 2013; Moon et al. 2013; Soltanzadeh et al. 2014;

Table IV. Representative WSN Deployments Employing WET and Their Key Characteristics

Technologies		Setting	Performance	Efficiency	Range	Literature reference
Acoustic waves		Biomedical	100 W	54%	3 cm (Skin)	Charthad et al. [2014]
		Biomedical	62.5 *m*W	21-35%	105 mm (Skin)	Arra et al. [2007]
		Through metal wall	30 *m*W	–	7 mm (Aluminum)	Kluge et al. [2008]
		Through metal wall	0.25 W	–	5.7 cm (Steel)	Shoudy et al. [2007]
Magnetic fields	Resonant inductive coupling	Through concrete	–	5.3%	40 cm (Concrete)	Jonah and Georgakopoulos [2011]
		Underground sensors	–	0.8%	5 m (Air)	Hancke and Vorster [2014]
Electro-magnetic radiations	Microwave /RF transmissions Visible light	Through air	45 *m*W	1.5%	10 cm (Air)	Peng et al. [2010]
		Through air	7 *m*W	–	100 m (Air)	Bhatti et al. [2014]
		Through air	85 *u*W	–	1.5 m (Air)	Wang et al. [2012]

Sun et al. 2012]. The problem, however, is still open, in that no established solution is available. The size restriction on the receiver antenna, which should be on par with the size of the WSN device, still represents a limiting factor. For example, Bhatti et al. [2014] show that a commercial 3W RF power transmission system [PowerCast 2009] can generate mW of power only at a few cm.

Reported experiences. Computational RFIDs [Gummeson et al. 2010], together with the recent push for highly miniaturized μW-level WSN platforms [Kuo et al. 2014], point to a class of systems that may benefit from WET through microwaves and RF transmissions. Powercast chips [PowerCast 2009] and the WISP node [Smith et al. 2006] represent concrete platforms available to evaluate the limits and applications of RF energy transfer in WSNs [Tong et al. 2010]. As an example, Peng et al. [2010] build a prototype system with a Powercast transmitter on top of a mobile robot and equip the WSN devices with a wireless energy receiver. An energy station monitors the energy level of the WSN nodes and routes the robot accordingly. Similarly, Tong et al. [2010], Li et al. [2011], and Dai et al. [2013] also study deployment configurations, scheduling, and near-optimal routing of a mobile node to wirelessly recharge WSN nodes using a Powercast transmitter. Mishra et al. [2015] show that multi-hopping is also possible when employing WET with RF transmissions, which may increase the operational range.

12. WIRELESS ENERGY TRANSFER: DISCUSSION

To provide a summarizing view of how WET is employed in WSN applications, Table IV shows representative efforts in this area, along with their key features. Based on these, we draw the following observations:

—WET using acoustic waves, due to its high permeability (**WET4**), is often employed to power sensors in sealed or inaccessible environments, such as biomedical implants and areas behind metal walls. The reported performance is in the mW scale with efficiency (**WET1**) from 21% to 54%. Compared to the general state of the art, these figures represent a best-case performance in real-world deployments. In contrast,

Table V. WET Against the Desirable Properties of Section 2

	WET technique				
Efficiency	**Acoustic**	**Inductive coupling**	**Resonant inductive coupling**	**Microwaves/ RF transmissions**	**Light**
Performance	Medium	Low	High	Medium	High
Form factor	Medium	Medium	Medium	Big	Small
Range	Medium	Medium	Low	High	High
Permeability	High	Low	High	Low	Low
Safety	Medium	High	High	Medium	High (diffused)/ Low (lasers)
Routability	No	No	Yes	Yes	Yes

the practical feasibility of WET using acoustic waves in WSN applications is limited by its operational range (**WET3**), which rarely exceeds a few cm.

—Magnetic fields as a means to implement WET also enjoy high permeability (**WET4**), yet through different materials than acoustic waves, enabling WSN deployments underground or inside concrete structures. Compared to WET using acoustic waves, however, the attainable efficiency (**WET1**) is one to several orders of magnitude lower, while the operational range (**WET3**) is distinctively larger only when transferring through air. In the few cases where performance figures are indicated, mW scale energy transfers are reported across tens of cm.

—WET through electromagnetic radiations shows different performance when using visible light or microwaves/RF transmissions. Because of low permeability (**WET4**), WSN applications leveraging this technique are mainly limited to transfers through air. Efficiency (**WET1**) is comparable to that of magnetic fields, whereas the operational range (**WET3**) may reach hundreds of m while keeping mW-scale performance at the receiver. In WSN applications, this performance is often achieved by means of a directional beam, for example, using laser light, provided line of sight and an accurate transmitter-receiver alignment is attainable.

Table V concludes the discussion by qualitatively illustrating how different WET techniques cater for the desirable properties of Section 8. Again, we do this independent of their reported use in WSN applications to foster new directions regardless of already existing efforts. Key observations are as follows:

—Most efficient (**WET1**) techniques appear to be magnetic fields using resonant inductive coupling and visible light. The former enjoys better permeability through solids (**WET4**), whereas the latter has greater operational ranges (**WET3**).

—WET using visible light may also provide small form factors (**WET2**) compared to all other techniques, but it may pose safety (**WET5**) hazards when using lasers, due to the high energy density.

—WET using electromagnetic radiations is, in principle, most suited to scenarios needing long operational ranges (**WET3**), also because of the routability (**WET6**) properties that both visible light and microwaves/RF transmissions enjoy.

—High permeability (**WET4**), in contrast, is provided by acoustic waves and resonant inductive coupling, especially through solids. Only the latter is routable (**WET6**).

The following section opens the last part of the article, providing a set of overarching considerations that begin with mapping energy-harvesting and wireless transfer techniques back to the characteristics of target WSN deployments.

13. MAPPING WSN ENVIRONMENTS TO HARVESTING AND TRANSFER TECHNIQUES

The discussion thus far points out the applicability of energy-harvesting and wireless transfer techniques as a function of the target environment. In light of this discussion,

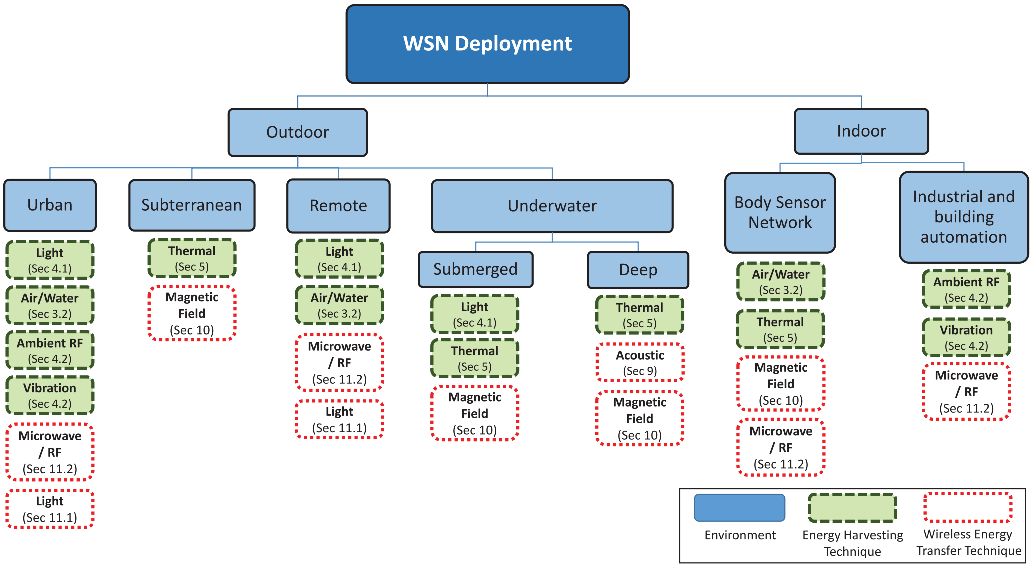

Fig. 17. Mapping from WSN deployment environments to energy harvesting and wireless transfer.

we give the reader a set of guidelines to gauge the most appropriate solution based on the characteristics of the deployment. To this end, we distill a set of paradigmatic WSN deployment environments and map energy harvesting and wireless transfer back to them. Figure 17 pictorially illustrates the mapping.

13.1. Outdoor Environments

Early literature on battery-operated WSNs included numerous reports on outdoor deployments with little infrastructure support [Estrin et al. 1999, 2002; Singh et al. 2007; Tolle et al. 2005], including remote [Mainwaring et al. 2002], harsh [Lorincz et al. 2006], underwater [Heidemann et al. 2006], and subterranean [Markham et al. 2010; Thiele et al. 2008, 2010] locations. Outdoor deployments in urban areas also have considerable attention [Filipponi et al. 2010; de Alvarenga et al. 2014; Wan et al. 2012]. Each of these environments features distinctive characteristics that may alter the choice of the most suitable energy-harvesting or wireless transfer solution.

Outdoor environments → remote. Locations that lack human infrastructure in the vicinity are, for example, forests, deserts, glaciers, and volcanoes. In such locations, solar light remains perhaps the single most likely natural source of energy, which can be extracted as explained in Section 4.1. Nonetheless, other forms of energy harvesting may be feasible in these locations, such as harvesting energy from air or water flows, as illustrated in Section 3.2, and from thermal gradients, as discussed in Section 5.

WSNs deployed in remote environments may also benefit from WET. The availability of the aforementioned energy sources, indeed, can vary significantly, both temporally and spatially. Larger harvesting units can be deployed at locations with abundant harvestable energy, later re-distributed through WET. While other techniques might also be suitable in specific scenarios, the potentially large distances favor WET using lasers or microwaves, illustrated in Sections 11.1 and 11.2, respectively. In the long term, it is expected that systems will be deployed to harness energy over great distances; for example, if technology would allow us to send satellites into orbit that beam energy wirelessly down to earth, like it happens today for data signals available worldwide, such as the GPS [Shinohara Shinohara].

Outdoor environments → underwater. Underwater sensor networking differs from traditional WSNs on many accounts; for example, because of the use of acoustic waves for data transfer, which results in significantly lower bandwidth and higher latencies. The need for energy harvesting and wireless transfer is natural in these environments, since battery replacement is highly undesirable or even impossible.

Submerged WSN deployments, that is, located near the water surface, include applications such as monitoring water quality in rivers or lakes and checking for occlusions in home water pipes [Metje et al. 2012; Chen et al. 2013; Campbell et al. 2014]. Since these deployments are close to the surface, it is natural to harvest kinetic energy from water waves, as described in Section 3.2. Moreover, solar energy can be harvested at the surface and transferred to the nodes below using water-permeable WET technique such as acoustic waves, illustrated in Section 9, or inductive resonant coupling, as explained in Section 10. WET through electromagnetic mechanisms, described in Section 11, is ruled out due to the high attenuation through water.

Deep underwater deployments observe phenomena such as sub-sea oilfields [Heidemann et al. 2006] and enjoy little or no direct access to ambient energy sources. In these scenarios, the only realistic—yet not entirely practical to date—solution is to deploy a large energy source, like a radioisotope thermoelectric generator, on the ocean floor that can transfer energy using one of the water-penetrating WET techniques.

Outdoor environments → subterranean. WSN deployments are also reported in underground colonies of animals [Markham et al. 2010; Thiele et al. 2008, 2010], inside mines [Li and Liu 2009], and in agricultural fields [Kahrobaee and Vuran 2013]. Harvesting opportunities in these locations are minimal, with the exception of vibrational and thermal sources. Vibrational sources may emerge due to movements above ground that propagate through the soil, harvested using approaches presented in Section 3.1. As an example, in agricultural fields, shallow subterranean deployments may benefit from the vibrations generated by regular movement of heavy machinery, including seeders, harvesters, and mobile irrigation systems [Kahrobaee and Vuran 2013]. Thermal sources appear due to differences between soil and ambient temperatures. The extraction techniques described in Section 5 are usable there.

WET based on magnetic fields is arguably the most suitable mechanism to supply energy in subterranean deployments, due to permeability in soil. For example, a source above ground may employ inductive resonant coupling to transfer energy through soil at depths of 10–40cm [Menon et al. 2013], employing the techniques illustrated in Section 10. The natural mobility of subterranean fauna under observation [Link et al. 2010], for example, whenever animals come out and go back into burrows, can be exploited to transfer bulks of energy, later redistributed to nodes inside burrows using any of the short-range WET techniques, such as inductive resonant coupling. Similarly, for deep underground operations, such as in mines, an energy source that we may deploy in situ may employ the routability features of WET using magnetic fields, as described in Section 10.

Outdoor environments → urban. These environments are characterized by an abundance of infrastructure for energy, transport, and living. Thus, they offer a host of sources for energy harvesting, with the energy generated not just by nature, as in the case of solar light and wind, but also by humans and their activities, as in the case of RF transmissions (discussed in Section 4.2), water flows (reported in Section 3.2), or vehicle-induced vibrations (as in Section 3.1).

WET for WSNs in urban environments is, however, arguably nontrivial. Current trends indicate the possibility of eventually deploying a low-energy wireless powergrid. Cities can deploy power beaming systems; for example, using microwaves, described in Section 11.2, at locations that have best solar irradiation to gather energy and re-distribute it within a mesh of energy-distributing nodes. One such example is the “array of things” deployment in Chicago [Things 2014], where energy-distributing nodes deployed on top of light poles use microwaves to hand out harvested solar energy. Urban environments, nonetheless, impose strict safety (**WET5**) requirements, ruling out unsafe WET technologies, such as laser, in densely populated areas.

13.2. Indoor Environments

Market needs progressively drove the deployment of WSNs in structured indoor environments. These installations serve a multitude of purposes; for example, providing means to extend the scope and granularity of building automation systems [ZigBee 2015; Z-WAVE 2015] and replacing existing industrial wired sensors [HART Communication Foundation 2015; International Society of Automation 2015]. WSN-powered medical and smart-health applications also have emerged; for example, in the form of body sensor networks (BSNs) providing one’s vital signs for real-time analysis [Cong et al. 2009; Zhang et al. 2010]. Similar to the outdoor case, every such environment bears distinctive characteristics.

Indoor environments → industrial and building automation. Most of these environments enjoy an existing wired energy distribution infrastructure. Still, energy harvesting and wireless transfer remain desirable for a number of reasons; for example, to exploit renewable energy sources or to enable rapid prototyping.

In factory environments, vibrations due to moving machines provide an abundant source of kinetic energy. The corresponding extraction techniques, as discussed in Section 3.1, are both sufficiently mature and provide reasonable performance. In buildings, numerous other harvestable energy sources exist, such as air flows induced by the operation of ventilation systems and RF transmissions due to WiFi and cellular networks. Extraction techniques pertaining to the former are sufficiently developed, as discussed in Section 3.2. Differently, the state of the art in rectenna design, still battling with the need to miniaturize the devices as discussed in Section 4.2, is arguably not quite at a level of widespread adoption.

WET in such energy-rich environments might facilitate seamless deployment of WSN nodes. With the advent of commercial, high-intensity WET solutions [WiTriCity 2015; Energous 2015], using resonant inductive coupling, discussed in Section 10, or RF transmissions, described in Section 11, one may foresee the availability of a full energy infrastructure within buildings. WSNs installed therein can thus primarily focus on the application requirements and not on energy-conservation issues, as these technologies are provisioned for multi-watt consumer appliances, such as TVs and mobile phones, and thus easily support the mW requirement of WSNs.

Indoor environments → body sensor networks (BSNs). Applications employing BSNs are often required to operate unattended for months or years, and yet they often exhibit varying degrees of mobility and severe form factor constraints. These characteristics make applying traditional battery technology very difficult. Because of this, BSNs are often coupled with energy-harvesting and wireless transfer techniques.

For example, kinetic energy sources including muscle movements and blood flows, as well as thermal energy sources such as temperature differentials, are well suited to energy harvesting in such networks. The corresponding extraction techniques, described in Section 3 and 5, are able to match the form factor constraints without impacting the node mobility. WET is also a practical solution when monitoring patients inside hospitals or at home, mainly because they are expected to be restricted in their movements, and thus remain within the range of WET mechanisms such as magnetic resonance, as described in Section 10, or light, as explained in Section 11.1. It is even conceivable that purely inductive coupling is used to transfer energy for sub-cutaneous devices, using a robotic infrastructure in a patient's vicinity [Seo et al. 2012].

14. RESEARCH AGENDA

Battery-powered WSNs manifested new challenges out of the necessity to manage *finite* energy budgets against sensing, computation, and communication needs. Energy harvesting and wireless transfer fundamentally redefine these challenges, as the assumption of a finite energy budget is replaced with that of potentially *infinite*, yet *intermittent*, energy supply. This profoundly impacts every aspect of wireless sensor networking, ultimately including the pattern of operation. This will eventually transform from the traditional sense-compute-transmit to a *harvest*-sense-compute-transmit-*share*, that is, beginning and ending with energy- and not data-related tasks.

Based on this observation, we identify four major areas worth additional research efforts. We discuss next the issues that we maintain are to be researched in every such area, providing specific directions for future work.

1. Hardware design. In energy-harvesting WSNs, the input power is a function of energy availability in the environment and thereby heavily fluctuates. Electronics employed in battery-powered WSNs, on the other hand, feature a narrow *operational power spectrum*, that is, the range of different power inputs the electronics can withstand. This makes traditional electronics ill suited to energy-harvesting WSNs [Yang et al. 2014]. To make things worse, the same kinds of electronics often present high surge current requirements, possibly preventing WSN nodes from (re-)booting even if energy is available.

These considerations influence every aspect of a node's hardware design, from sensors to memory to processors to radios. New designs are thus required that: (i) can cope with highly variable supplies of energy and (ii) reduce the gap between a node's energy requirements and the generation capacity of the harvesting unit. For example, multiple operational states of the hardware, with varying performance levels and power requirements, can be defined to stretch the operational power spectrum. Efforts are currently undergoing to achieve these objectives [Kuo et al. 2014], yet the challenge is arguably far from being fully addressed.

2. Networking energy. The integration of energy harvesting in traditional WSNs does not pose significant challenges, as it requires extensions—in the form of a harvesting unit—that only impact individual nodes.

The case differs when applying WET. Energy, previously considered as a node's local commodity, now becomes a deployment-wide shareable resource. How to concretely take advantage of this conceptual leap is still quite unclear. For example, one needs to understand how to schedule energy transfers; which amount of energy to transfer; and to whom to transfer energy, which may further require accurate localization when using directional techniques. Some recent work started exploring these questions [Zhu et al. 2012, 2010; Li et al. 2011], providing early evidence of the opportunities enabled by embedding a notion of a energy distribution as a first-class concept that affects both the sensing functionality and communication stack of WSNs. Data and energy networking will need to be co-designed, and an *energy management stack* will need to be integrated to serve energy distribution requests. The possible design choices are also several. For example, scheduling energy transfers is achievable with static policies like *earliest-dead first* or based on application-specific requirements.

Because of the characteristics of current energy-harvesting and wireless transfer technologies, we may also need to redefine the roles of different nodes. A homogeneous network model, which considers every node to be equally capable of energy harvesting and wireless transfer, is hardly feasible. As discussed in Section 8, for example, deployment constraints may create significant imbalances in the ability to harvest energy. As a result, a tiered network model is probably more appropriate, similarly to RFID systems. More capable nodes will be responsible for generating energy, perhaps from a renewable ambient source, and for transferring it to less capable in situ devices that harvest and consume it. A similar model was repeatedly advocated for data networking [Estrin et al. 1999; Schmid et al. 2010]; the integration of an energy management stack is only going to make these efforts more relevant.

3. System software. The ability to harvest energy from the ambient is also changing how the system software operates, including operating systems and data networking. In addition to being energy aware, systems must be *supply aware*, that is, able both to accommodate intermittent supplies of energy and to withstand power outages.

Operating systems must be capable of stretching an application's processing across periods of energy unavailability, letting the system *resume*, and not restart, the previously running tasks. Efficient solutions to this problem, however, are far from straightforward. For example, periodically checkpointing the entire system state for later resumption is likely inefficient. Strategies must be conceived to decide when to checkpoint based on the current system state and remaining running time, doing so with minimal disruption of the application's processing. Some works in the area of computational RFIDs [Ransford et al. 2011] resonate with some of these considerations, yet the specific solutions are difficult to port to WSNs because of the significant degree of decentralized processing that characterizes the latter. Efficient state retention techniques for modern WSN platforms exist [Bhatti and Mottola 2016], yet it is also likely that only parts of the system state are to be checkpointed or that state information bear time-dependent validity constraints; for example, when using sensor data to enact decisions on the environment. Developers need to be given ways to express these aspects in their programs; for example, through proper language constructs.

Challenges also exist for data networking. A better understanding of how existing protocols are influenced by periods of energy unavailability is required in the first place. It may be argued, for example, that nodes running out of energy and later resuming are analogous to nodes crashing and eventually being replaced. This argument, however, plainly depends on the time scales at hand. A more robust approach would dissect the relevant networking mechanisms, such as neighborhood management and packet forwarding in routing protocols, and possibly design ways to adapt these mechanisms to an intermittent computing pattern. *Anytime algorithms* [Zilberstein 1996]—returning a valid solution at any point in their execution—may provide a means to this end.

The OS-level and networking challenges meet when thinking of the issues possibly arising whenever the state of a node resuming after a period of energy unavailability shows *inconsistencies* against the state of nodes enjoying different energy supplies. This may create ripple effects that ultimately worsen performance, as already recognized in the literature in the context of software failures [Chen et al. 2009]. In principle, addressing these issues would require coordinating checkpoints on a system- or neighborhood-wide scale, making sure that nodes resume from a state that remains meaningful compared to that of other nodes. These considerations may bring back to life a whole body of work on distributed checkpointing [Koo and Toueg 1986], now cast in a domain of resource-constrained devices operating across multi-hop topologies.

4. Environment models and tools. The need for accurate environment models is clear already in battery-operated WSNs. For example, models of wireless propagation in a given deployment may serve simulators or pre-deployment tools that allow users to establish performance vs. cost tradeoffs. Obtaining this kind of model is a challenge, as the relevant environment features are difficult to identify.

In a similar vein, obtaining models of energy propagation or availability in a given environment is also complex. As for energy propagation, considerations akin to wireless transmissions largely apply. In the case of energy harvesting, the general characteristics of an area may be known; for example, Southern California is sunny and the Pacific Northwest less so. However, available energy in a specific location varies greatly over short distances and time. A paradigmatic example is that of sun-flecks: rapidly moving solar spotlights on the forest under story [Leakey et al. 2005]. Their presence or absence can greatly change solar irradiation on ground, yet their patterns are surprisingly complicated.

Confronted with these challenges, we need to conceive suitable environment models and incorporate them in concrete tools to help users understand the energy nature of the environment, enable pre-deployment simulations to understand performance vs. cost tradeoffs, assist debugging at deployment time, and enable remote tuning and adaptive management of network-wide energy. Designing such tools, in turn, raises several questions; for example, how can we trade accuracy vs. processing times in the simulation of energy-harvesting WET-enabled WSNs? How long do we need to observe a site to gain sufficient information for feeding the models? What level of spatial granularity is required to obtain trustful estimates for a given site?

15. CONCLUSION

Energy harvesting and wireless transfer are gradually finding their way in WSNs. The former can mitigate the energy constraints of traditional battery-powered WSNs and possibly achieve the longstanding vision of perpetual deployments. However, the feasibility of a particular energy-harvesting technique is deployment specific. WET can overcome these limitations by provisioning an energy-deficient environment with abundant harvestable energy. Because of these crucial features, a plethora of research work appeared on these subjects.

In this article, we defined desirable properties that energy-harvesting and wireless transfer techniques must present to enable their use in WSN applications, and we surveyed and classified existing solutions and argued about their applicability in different deployment environments. Although the initial upsurge in these fields is clearly visible, a lot remains to be researched to reap maximum benefits. For example, the gap between the efficiency of exiting techniques and the energy demands of WSN nodes is to be reduced further. Moreover, WET makes energy become a network wide shareable resource, fundamentally impacting the pattern of system operation. As a result, a number of further research directions open up involving hardware design, networking energy, system software, environment models, and tools.

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