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Energy Harvesting and Wireless Energy Transfer

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***Abstract*— 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). Ambient energy harvesting may prolong the systems' lifetime, or possibly enable perpetual operation. Also wireless energy transfer allows systems to decouple the energy sources from the sensing locations, enabling deployments previously unfeasible.The discussion is instrumental to providing a foundation for selecting the most appropriate energy harvesting or wireless transfer technology. [3].**

***Index Terms*— Wireless energy transfer, energy harvesting.**

I. INTRODUCTION

The idea of wireless power transfer (WPT) has been around since the inception of electricity. In the late 19th century, Nikola Tesla described the freedom to transfer energy between two points without the need for a physical connection to a power source as an "all-surpassing importance to man". A truly wireless device, capable of being remotely powered, not only allows the obvious freedom of movement but also enables devices to be more compact by removing the necessity of a large battery. Applications could leverage this reduction in size and weight to increase the feasibility of concepts such as paper-thin, flexible displays, contact-lens-based augmented reality, and smart dust, among traditional point-to-point power transfer applications. Notwithstanding recent developments in battery fabrication, this resulted in increasingly smaller amounts of available energy. [2].

II. MAJOR ENERGY HARVESTING TECHNOLOGIES

Our environment provides several virtually cost-free sources of energy that can be harvested if appropriate devices are adopted. .Energy harvesting communications have recently emerged as a promising paradigm to supply power to network terminals by letting them scavenge energy from external resources. .These sources are already exploited to scavenge power for human activities, hence it seems legit to envision their exploitation in the context of wireless communications as well. Harvesting or scavenging mechanical energy from the surroundings is a potential strategy to develop self-powered sensor nodes and electronic devices.

There are many mechanisms by which the energy can be harvested. .The most efficient technique for mechanical energy harvesting is Piezoelectric Energy Harvesters. Piezoelectric mechanism is the most common and well researched technique in the area of mechanical energy harvesters.

These devices work on the property of material known as piezoelectricity. It is the property of the materials

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to produce charge (or voltage) when stimulated by a mechanical stress. The most efficient way for Electromagnetic Energy Harvesting is based on Faradays Law. Electromagnetic mechanical energy harvesters work on the principle of Faraday's law of induction. Majority of the electrical motors, transformers, inductors and generators are based on this fundamental operating principle. Faraday's law states that the voltage or electromotive force (emf) generated in a closed circuit directly proportional to the total flux through the closed loop circuit.

III. NEAR FIELD AND FAR FIELD

A. Near-Field Transfer

Near-field transfer is based on the coupling of two coils within the distance of the coils' dimension. In fact a transformer is transferring energy wirelessly through magnetic field coupling, although it was invented more than 100 years ago. But if you remove the iron core and move the two coils apart, the transfer efficiency drops drastically. That is why the two coils must be put close enough to each other. This kind of method is already commercialized. For example, most electric toothbrushes today are using wireless chargers, which are much safer than cable chargers in wet environment.

However, if the transmitter and receiver coils have the same resonant frequency, which is determined by the material and shape of the coil, transfer efficiency will decrease much more slowly when they are moved apart.

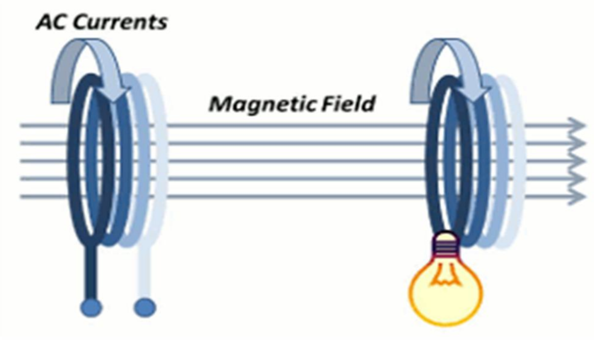

Fig 1

B. Far-field Transfer

To transfer energy wirelessly over long ranges, far-field transfer is used. Far-field transfer is based on electromagnetic wave which is radiative. Different methods use electromagnetic waves within different wave band. In the early times, experiments were carried out with radio and microwaves, around 1GHz. [4] Electric energy is transferred to a strong beam of radio or microwave by a dish-like antenna, travels through the atmosphere and then received by another antenna which transfers it back to AC electric current.

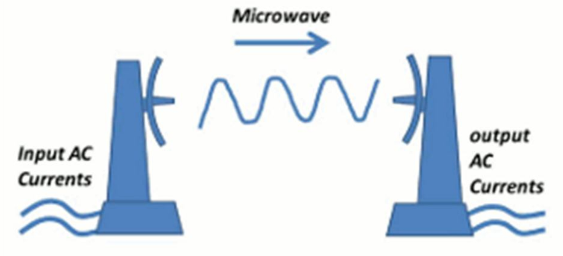

Fig 2

IV. ENERGY HARVESTING

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. [3]

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:

WSN1: <u>High Energy Density</u>: 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.

WSN2: <u>High Efficiency</u>: 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.

WSN3: <u>Small Form Factor</u>: 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.

WSN4: <u>High Robustness</u>: 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.

<u>Low Cost</u>: The harvesting equipment should be attainable at low cost, not to significantly impact the system's total cost of ownership.

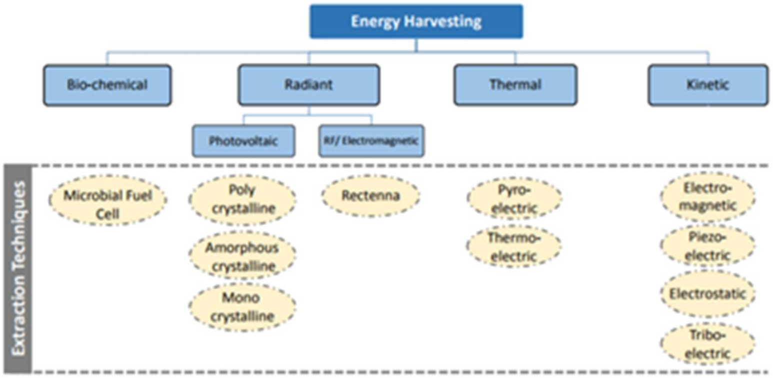

Fig 3. Energy source (rectangular blocks) and their extraction techniques (oval blocks)

V. ENERGY HARVESTING – ELECTROSTATIC SOURCES

Electrostatic energy harvesters work on the principle of variable parallel plate capacitor. The mechanical energy available in the surroundings is used to change the gap between two parallel plates, which together form the capacitor system. This change in the gap or relative position of the two plates leads to flow of charges in the external load connected across the two plates. The physical mechanism of the electrostatic energy harvesters can be distinguished based on the type of relative motion between the two plates. Electrostatic energy harvesters can be divided into categories: (i) using external voltage supply for biasing (ii) using electrets. The first category of the devices rely on an external bias to create a potential difference between the two parallel plates. In the second type of device, electrets are used to create a potential difference between the parallel plates. Electrets are essentially dielectric materials with permanent electrical polarization analogous to permanent magnet.

VI. 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 selfwinding 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.

VII. ENERGY HARVESTING – RF TRANSMISSIONS

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 radio-frequency (RF) transmissions.

Extracting energy from pre-existing radio-frequency (RF) transmissions recently received much attention, as shown in Figure 1, due to the increasing pervasiveness of cellular stations, FM radios, and Wi-Fi 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. 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.[3]

VIII. 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.[3]

IX. WIRELESS ENERGY TRANSFER

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.

Recent advancements in wireless energy transfer (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.

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, 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.

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 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.

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.

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. [3].

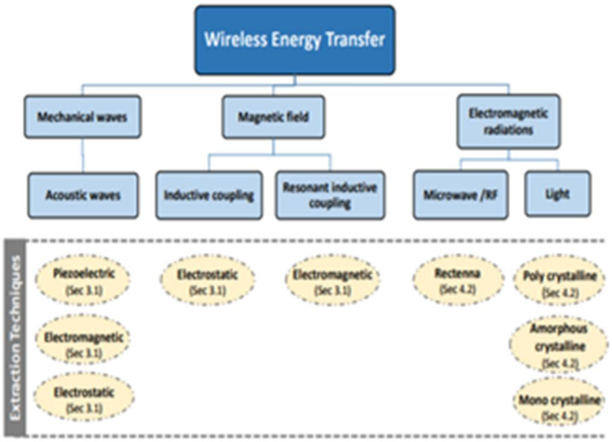

Fig 4. Existing transfer mechanisms and corresponding harvesting techniques

X. Benefits Of Wireless Power

- Maintaining direct connectors (like those in the traditional industrial slip ring).
- Greater convenience for the charging of everyday electronic devices.
- Safe transfer of power to applications that need to remain sterile or hermetically sealed.
- Electronics can be fully enclosed, reducing the risk of corrosion due to elements such as oxygen and water.
- Robust and consistent power delivery to rotating, highly mobile industrial equipment.
- Delivers reliable power transfer to mission critical systems in wet, dirty and moving environments.

XI. 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. Out 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 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. [3]

XII. Wireless Energy Transfer – Magnetic Fields

WET techniques using magnetic fields mainly leverage energy harvesting based on electromagnetic effects 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. [3]

XIII. 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 distinction also impacts 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 infra-red spectrum—mainly visible light—pack sufficient photonic energy to use extraction techniques based on the photoelectric effect.

Electromagnetic radiations at frequencies higher than visible light carry energy that can be gained back using a rectenna. This kind of WET is extensively studied for long-distance energy transfers—in the order of several Km— and for high-power systems. 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. [3]

XIV. EFFICIENCY

Efficiency is measured in a general sense as the amount of power (as a percentage) that is transferred from the power source to the receiver device i.e. a wireless charging system for a smartphone with 80% efficiency means that 20% of the input power is being lost between the wall socket and the battery for the smartphone. The formula for measuring operating efficiency is:

$$\text{Efficiency} = \frac{\text{DC Power OUTPUT}}{\text{DC Power INPUT}} \text{ x } 100\% \quad \text{CAN}$$

When a metallic or electrically conductive material (i.e. carbon fiber) is placed within close proximity of an electromagnetic field, the metallic object will absorb the power from the magnetic field, and heat up as a result. This, in turn, affects the efficiency of the system due to power being lost through absorption. This is how induction cooking works – inefficient power transfer from the cooktop creates heat to enable cooking. This post on wireless charging and induction cooking provides a detailed explanation on this relationship.

XV. FUTURE PERSPECTIVES AND PRACTICAL APPLICATIONS

Energy harvesting for wireless communication networks is a new paradigm that allows terminals to recharge their batteries from external energy sources in the surrounding environment. A promising energy harvesting technology is wireless power transfer where terminals harvest energy from electromagnetic radiation. Thereby, the energy may be harvested opportunistically from ambient electromagnetic sources or from sources that intentionally transmit electromagnetic energy for energy harvesting purposes. A particularly interesting and challenging scenario arises when sources perform simultaneous wireless information and power transfer (SWIPT), as strong signals not only increase power transfer but also interference. This article provides an overview of SWIPT systems with a particular focus on the hardware realization of rectenna circuits and practical techniques that achieve SWIPT in the domains of time, power, antennas, and space. The article also discusses the benefits of a potential integration of SWIPT technologies in modern communication networks in the context of resource allocation and cooperative cognitive radio networks.

Cellular Internet of Things in general and Sensor applications in particular:

a. Wirelessly connected “battery free” devices.
    i. Sealed environments (medical devices, moving parts, etc.).
    ii. Small size (as before + security).
b. Trickle Charging, High-function RFID.
c. Wearable devices.[1]

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.

A. 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-unsuited to energy-harvesting WSNs. To make things worse, the same kind of electronics of- ten presents high surge current requirements, possibly preventing WSN nodes from (re-)booting even if energy is available.

B. 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 is different 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.

C. 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 check pointing 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.

D. 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 trade-offs. Obtaining this kind of models 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 wire- less transmissions largely apply.[3].

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