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Enabling the Internet of Things through Energy Harvesting: A circuit-aware system synthesis-oriented analysis approach

A thesis submitted for the fulfillment of the
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Abstract

Powering wireless sensors has become a key challenge to enable the Internet of Things vision. A common approach to achieve this is to use Energy Harvesting. By means of this technology, sensors have access to an unlimited source of energy, which can extend their operation lifetime.

Unfortunately, typically the energy that is available surrounding the sensors is neither controllable nor predictable, showing significant variations in the expected harvested energy in terms of both space and time. This can cause the temporal disconnection of parts of the wireless network.

The objective of this thesis is to mitigate the undesirable effects of the spatio-temporal variations of the surrounding energy, by following a two-fold approach: first, to provide a high level understanding of the involved trade-offs in the design of a wireless sensor and the interconnecting network. Then, to synthesize an energy field to guarantee the required amount of ambient energy at the surrounding of the considered nodes.

The first part of the thesis starts by presenting a formal description of the environment. The derived energy model is first used to answer fundamental questions on throughput scaling and, then, to provide design guidelines for energy harvesting sensors. It is found that energy harvesting is a scalable solution to power and recharge IoT sensors, which require additional circuit design to guarantee their operation in energy scarce scenarios.

On the second part of this work, wireless RF power transmission from controllable Energy Transmitters (ETs) is considered as a feasible approach to synthesize an energy field to power sensors at-a-distance, hence tackling the lack of available ambient energy in spatial regions, at the cost of occupying the available wireless spectrum. Due to the limited transmission range of this approach, the use of multiple ETs to cover entire areas is required. We first discuss on the feasibility of synthesizing energy fields with multiple ETs. We show that powering those sensors with multiple ETs stands as a scalable approach, which presents a trade-off between the channel conditions and the energy multiplexing design complexity. We, then, present an opportunistic scheme to leverage the generated interferences of multiple ETs. Finally, we propose a joint energy and communi-

cation method to circumvent the imposed trade-offs of in-band multi-ET wireless RF power transmission.

Overall, we find that the analysis and design of wireless networked sensing systems, enabled by energy harvesting, and the development of novel wireless RF power transmissions schemes will play a key role in the future development of autonomous IoT deployments.

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Chapter 1

Introduction

Wireless networked sensing systems are the "invisible" enablers of pervasive communications, remote monitoring and surveillance, the Internet of Things, and of all those systems that are an increasingly essential part of our everyday life. Powering these systems is becoming the crucial challenge, as key requirements such as cost effectiveness, very small form factors and decade-long lifetimes are difficult to meet by using nodes that are battery-less or with low-capacity batteries. Hence, alternative sources of energy must be considered to tackle this problem.

A promising approach to perpetually operate the sensor systems is by acquiring the energy that is found in the close environment of the sensor. Physical phenomena, such as solar energy, vibration, human movement or electromagnetic RF waves have demonstrated potential as sources of energy, where sensors can rely on to autonomously run unattended tasks without the need of manual replacement of batteries. This has been generally referred as *Energy Harvesting* and it is defined as a process by which the ambient energy located at the close environment of the considered device is captured, converted into electrical current and stored for later use in powering the desired tasks of the device.

Energy Harvesting is being considered as the key-enabling-technology of the Internet of Things and promises to change the way the considered devices make use of the energy. Through this technique, the considered sensors have a time-unlimited access to a scarce source of energy, which relaxes the need for large energy storage units and manual re-charging or replacement, to guarantee a sufficient operation lifetime. Accordingly, a proper design of the electrical device, which aims at handling the temporal variations in access and demand of energy, brings several benefits in the considered IoT deployment scenarios, such as size reduction, node placement in inaccessible locations, reduction of maintenance costs and an increase on the network operation lifetime.

Unfortunately, the energy that is available at the close environment of the sensing system is not controllable, and often not even predictable, hence showing significant variations in the expected harvested energy in terms of both space and time. In this sense, spatial energy shadowing causes that certain areas of the network may render disconnected from normal operation, whereas temporal fadings may temporarily inhibit sensing operations, temporarily interrupt the network operation or to cause excessive traffic delays.

For this reason, two alternatives raise as a measure to guarantee an uninterrupted operation. On the one hand, defining models to analyze and proper design both sensing systems and IoT networks are required. The aim of these models needs to cover, among others, battery dimensioning to mitigate temporal variations in the energy access and optimal routing and traffic balancing to mitigate spatial variations of the available energy. On the other hand, wireless RF power transmission from controllable *Energy Transmitters* (ETs) stands as a feasible, artificially generated source of energy to power sensors at-a-distance and to tackle the lack of available ambient energy in spatial regions. Given that RF propagation is affected by severe path-loss, the transmission distance of a wireless RF power transmission link is rather limited to just a few meters of distance, hence, multiple deployments of ETs that coordinately transfer energy towards the sensing systems are usually considered to cover entire networking areas.

The analysis and design of energy-harvesting-enabled wireless networked sensing systems and the development of novel highly-efficient wireless RF power transmissions schemes have significantly attracted the attention of the research community at many design layers. The topics that have been mostly set to tackle range from the design of energy harvesting transceivers and circuits, the impact of these in the sensor performance and the eventual network operation, the design of energy harvesting alternatives specifically suited for wireless RF energy transmission, coordination among multiple ET entities and the coexistence of simultaneous transmission of energy and data.

1.1 Motivation and Objectives

Energy harvesting and Wireless RF power transmission are research fields that have been treated as separated problems, where each has presented their own research challenges and associated trade-offs.

However, the fact that both approaches pursue a common objective, that is to autonomously recharge the networked systems, along with the conceptual difference based on acquiring energy which is either exogenous or endogenous of the system under study, brings the following open question: *Can we leverage the acquired knowledge in the study of physical energy harvesting phenomena to design Wireless RF power transmission schemes?* To answer this question this thesis is separated into two parts. The former refers to energy harvesting and aims at *analyzing* existing ambient energy in the form of an energy field. The latter refers to wireless RF power transmission and aims at *synthesizing* arbitrary energy fields with the help of multiple ETs that are deployed over the networking area.

1.1.1 Energy Harvesting

Interrelating the separated layers in the design of a complete energy harvesting enabled communication system throughout a vertical approach is still a pending challenge. As a result, several works analyze particular use-cases and provide quantitative results, which are hard to extrapolate when the conditions of the problem differ. The lack of qualitative trade-offs hinders the mutual understanding between both network and circuit communities and, hence, hindering design guidelines of critical circuit and system components.

Accordingly, generic feasibility studies that aim at relating the trend between tangible magnitudes are missing, such as the relating available input power at the node locations or number of deployed systems in a IoT to metrics for network and communication evaluation, such as the throughput of a network. In these lines, answering simple questions, such as: *How does the throughput of a network varies when the deployed nodes start failing?* need to be addressed, regardless of the non-triviality of its answer.

Objectives

The scarce nature and poor predictability of the energy sources requires additional efforts during the design stage. In this direction, the objectives of this thesis are:

- To provide a formal description of the energy harvesting process by proposing a general-purpose energy model. This model needs to capture the spatio-temporal variations of the ambient energy, as well as the node sensor system implications.
- To study the scaling laws on the capacity of the network throughput. This study assesses the viability using energy harvesting as the unique source of energy of the deployed nodes. It provides a high-level understanding of the energy harvesting process, its implications on the network performance and the imposed design trade-offs.
- To study the implications of the spatio-temporal variations of the surrounding energy, and to analyze the performance of mulit-EH and self-tunable EH as feasible solutions to circumvent their associated challenges.

1.1.2 Wireless RF Power Transmission

In a many-to-many wireless RF power transmission set-up for the IoT, where more than one ET delivers power to multiple sensors, RF waves radiated from these systems may interfere with each other at the receiver end if these are transmitted in the same frequency band. Devising energy multiplexing methods to avoid the destructive interference is still a pending challenge. However, despite these methods, the use of multiple ETs to cover an entire area of interest leads to concerns of scalability [144].

In order to design cost-effective communicating systems, the RF spectrum must be shared for both power and data transmissions. This reduces the need of duplicated antennas and hardware. Unfortunately, alternating between tasks may seriously affect network operation and performance. In fact, Time multiplexing between both tasks reduces, not only the eventual transmitted power, but also the idle time for data communications. As such, scheduling data transmissions in constrained time-slots increases the protocol complexity. For this reason, devising methods for energy provisioning without affecting data communications appears to be the challenge that the research community has most recently set to tackle [48].

Objectives

The deployment of multiple ETs to cover entire networking areas imposes several research challenges. In this direction, the objectives of this thesis are:

- To study the scaling laws of the cumulative power that is injected in the network. This study assesses the viability of using wireless RF power transmission from multiple ETs. It provides high-level understanding of the wireless RF power transmission process, as well as the design considerations of the energy multiplexing approaches, depending on the physical environment and the channel quality.
- To propose an energy multiplexing method that constrains the protocol complexity, while it improves the transmission of energy.
- To design a method to concurrently enable reception of power (from an ET) and information (from neighboring nodes) in an in-band fashion. This pursues an improvement of the network performance, without incurring into additional hardware and protocol complexity.

1.2 Thesis overview and contributions

Along this work, several tasks are placed in order to interrelate the multiple layer design of energy harvesting systems and to enhance the transmission of energy. The realized tasks and contributions are shown in Fig. 1.1. Accordingly, the overall content is divided into two parts, namely energy harvesting (analysis) and wireless RF power transmission (synthesis). In the former, first an energy model is derived that is necessary to derive the remainder contributions. Then, an analytical expression to bound the per node throughput capacity in a wireless network, when this is powered by energy harvesting is derived. Finally, design space exploration of energy harvesting sensors is proposed, tackling, spatio-temporal correlation of the energy and both multi-source and self-tunable energy harvesters. In the latter, an analytical expression to justify the use a

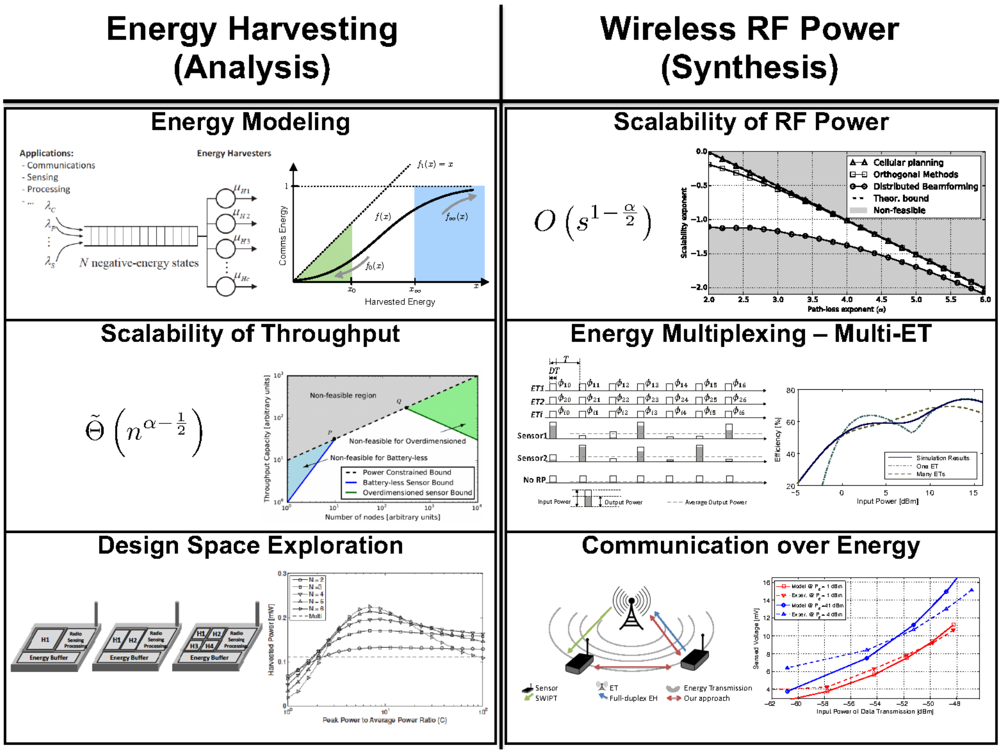

Figure 1.1: Overview of the proposed contributions in this thesis.

multi-ETs as a scalable solution to extend the coverage of deployed IoT. Then, an energy multiplexing method to leverage multi-ET interference is presented. Finally, a method to permit simultaneous wireless charging and in-band data communication is presented.

The aforementioned contributions are described in more detail next.

1.2.1 Energy Harvesting Tehniques for WSN

The first part of this work aims to develop a generic theory to model and characterize nodes and networks powered by a generic energy harvesting source. The topics that are covered here are:

Energy Model

Because energy harvesting and wireless RF power transmission are usually considered as separated scenarios, it is needed to develop a generic, energy-source agnostic model to characterize the access of energy at the eventual sensor devices. Hence, this model needs to cover two separated aspects. On the one hand, a generic model for the ambient energy is required, such that it simplifies the notation and helps the understanding of the energy harvesting process. On the other hand, a model to characterize the management of this energy, once the energy is harvested, needs to be further investigated. As such, this model needs to also consider the transmission patterns, statistics of the energy at the reception and internal efficiencies of the sensor.

By considering this model, we are able to define important metrics and concepts that will stand as the basis of the remaining work presented in this thesis. Among other important concepts, this model defines: the spatio-temporal correlation between the energy that is harvested at the node locations; the energy path function of a node device that bridges the communication requirements to the available energy in the environment, and the Energy-Erlang (E2), a statistical unit to handle energy resources. It is noteworthy that the proposed model also has multi-source energy harveting capabilities, such that modeling the operation of complex sensors, powered by a set of different energy harvesters is simplified.

Scalability of Throughput Capacity

The scalability of the per node throughput capacity of a wireless network was first bounded by Gupta and Kumar [50] showing that the throughput of a wireless network in bandwidth limited conditions *decreases* with the number of deployed nodes, n, as $\Theta(1/\sqrt{n \log n})$. At a high level, this bound showed that wireless networks are not scalable with the number of nodes, therefore constraining the deployment of nodes to just a few devices. More recently, a more closely related bound, was found for power constrained, free-space conditions, showing that the througphut *increases* with the number of deployed nodes, n, as $\tilde{\Theta}\left(\sqrt{n}\right)$, where $\tilde{\Theta}$ refers to the soft-order bound [98]. Given that the available resources in an energy harvesting enabled WSN are very limited, reaching a non-scalable bound would signify that a IoT network powered by energy harvesting cannot leverage node cooperation to enhance their performance, hence rendering impractical. Therefore, a scalabiltiy analysis to evaluate the throughput scaling with the number of nodes is required.

For this, a scalability analysis of the throughput capacity of an IoT powered by energy harvesting has been addressed. Throughout this analysis, we are able to derive a closed-form expression that relates the channel conditions, energy management at the sensors and the bounds in throughput scaling of the given network. By identifying the limits in the functionality of the nodes, we are able to understand at a high level the main trade-offs between the energy-communication conversion process, channel properties and eventual throughput.

Design space exploration of EH-powered nodes

As it is shown in the scalability analysis, the design of the energy management units of a sensor node has a decisive impact upon, not only of the sensor performance itself, but also on the overall network operation. Among other parameters, it has been shown that the capabilities of the energy harvester and the capacity of the energy storage unit play a very important role to ensure ideal throughput. In particular, it is shown that the quantity of harvested power directly impact on the throughput, whereas relatively small energy buffers can yield to non-resilient to node failure network operations.

For this, a study of the dimensioning of the energy harvester and energy buffer is provided. First, the impact upon the performance of the node, in terms of energy outage probability, with the size of the energy buffer is discussed. To derive these first results, a single energy harvester that optimally operates is assumed. Then, the joint energy harvesting - energy storage unit design is studied in a multi-source energy harvesting configuration. Finally, the idea of self-tunable energy harvesters is discussed and its performance and trade-offs are compared to multi-source energy harvesters.

1.2.2 Wireless RF Power Transmission

The obtained knowledge along the devoted chapters to energy harvesting aims at orienting the design of the energy network, defined as a set of deployed Energy Transmitters over the networking area. In addition, to leverage the properties of energy harvesting to implement sustainable IoT.

We describe next the primary contributions in the field of wireless RF power transmission:

Scalability of the Energy Field and Throughput Capacity

Extensive experimentation has shown a relatively short charging range of a single energy transmitter [36]. This has motivated the deployment of multiple ETs over large deployment areas [97] in WSN. Indeed, the presence of multiple ETs reduces the average propagation distance to the energy harvesting sensors, and thus decreases the attenuation level of the energy waves. However, it is still unclear that the combination of multiple transmissions can help reducing the overall transmitted power.

A first step towards the design of integrated energy networks and WSN refers to analyzing the scalability of the required energy in terms of the number of deployed ETs. At a high level, it is investigated whether the combination of multiple ETs can help reducing the overall transmitted energy or, if on the contrary, the deploying multiple ETs brings additional trade-offs and research problems that may preclude an eventual operation. As the main results show, increasing the number of deployed ETs for a given deployment is shown favorable in most daily environments. However, the design of multiple access methods for multi-ET transmissions i desired to achieve the best performance.

A Multiple Access Method for Multiple Energy Transmitters

Wireless RF power transmission from multiple ETs brings several trade-offs in the design, since simultaneous transmissions that may overlap over the medium can destroy each other. In particular, the constructive and destructive combination of RF waves generate very large peaks and drops of power in a non-controllable spatial-dependent manner. As a result, the underlying nodes, cannot guarantee a minimum of harvested power, hence interrupting their normal operation. The aim of existing MAC protocols for RF energy harvesting sensor networks with multiple ETs is to mitigate the impact of interferences.

For this, we introduce an energy multiplexing method, which aims at handling the simultaneous transmissions of power from the multiple ETs. This method relies on the fundamental assumption that efficiency is maximized when the input power varies in time as much as possible, since the energy harvesters operate with increasing efficiency as a function of the input power [105, 33, 100, 14].

Communications over Wireless Energy

The last step of this work is to effectively combine the wireless RF power transmission with the inter-node communication. Existing approaches devote separated access times for both operations when data communication and RF energy recharging occur in-band, raising architectural and protocol level challenges.

Accordingly, we propose a novel method to permit the concurrent transmission of data and energy that solves this problem. This allows ETs to transmit energy and sensors to transmit data in the same band synchronously. By considering this approach, nodes are able to avoid system duplicity at many design levels, hence potentially reducing manufacturing costs, power consumption and overall size.

1.3 Thesis Outline

The remainder of this thesis is structured as follows. The next chapter presents the necessary background that is required to understand and justify the main contributions of this thesis. Accordingly, it first overviews the main applications of energy harvesting and wireless RF power transmission for the Internet of Things. Then, it revises the current state-of-the-art of the proposed technologies. The following chapters, divided in two parts, namely energy harvesting and wireless RF power transmission, present the main contributions of this work. Chapter 3 introduces the developed models that have been considered to analyze and characterize the energy access and utilization. Chapter 4 addresses the scalability of wireless sensor networks powered by the use of energy harvesting. Chapter 5 studies the impact of non-uniform energy fields in terms of both temporal and spatial dimensions. These three chapters are based on the work published in [21, 23, 29, 31] and refer to the first part of this work referred as energy harvesting. The following chapters conform the wireless RF power transmission part of this work. Accordingly, Chapter 6 performs a feasibility analysis of multi-ET wireless RF power transmission and compares the ideal performance of the different energy multiplexing methods. This chapter has been submitted for publication in [26]. Chapter 7 presents an opportunistic method for energy multiplexing in a many (ETs)-to-many (sensors) scenario that leverages the circuital properties of existing energy harvesters to optimize their input-to-output power conversion efficiency. This chapter has been presented in [27, 28]. Chapter 8 proposes a method to permit simultaneous wireless RF power transmission and node-to-node communications in an in-band manner. The results of this chapter have been presented in [24, 25]. Finally, Chapter 9 concludes the thesis and presents ideas for future work.

Chapter 2

Related Work and Background

This chapter aims at contextualizing the contributions of this thesis. Accordingly, it first overviews the main applications and benefits of using energy harvesting and wireless RF power transmission for the Internet of Things. Then, it revises the current state-of-the-art of the proposed technologies.

2.1 Applications and Benefits

Energy harvesting and wireless RF power transmission are usually referred as key-enabling technologies for the Internet of Things. By leveraging the delivered power of such approaches, sensors will offer an unattended operation, reduce maintenance costs, reduce their size and enable applications that are considered unfeasible due to lack of practical accessibility.

Among the numerous applications of the Internet of Things, we find that energy harvesting and wireless RF power transmission techniques will have a determining impact in the following fields:

2.1.1 Perpetual Operation

The major benefit of energy harvesting and wireless RF power transmission in the field of the Internet of Things is provided by the fact that the communicating nodes are able to continuously harvest energy and to recharge their internal energy buffers.

To enable an almost uninterrupted operation of the deployed nodes, it is required to properly design the energy buffer capacity [23], transmission policies [7], scheduling [57] and communication protocols [6]. If any interruption occurs, the operating nodes must re-adapt the network operation until the failing nodes harvest sufficient energy and restart their operation [9].

2.1.2 Size Downscaling

As a consequence of the perpetual operation of the sensors, these no longer require large batteries to store energy for a few months of continuous operation [9]. On the contrary, these need to store just a small portion of the overall required energy, such that it powers the node while the ambient energy is shadowed.

A clear example of size downscaling is observed in solar powered sensors. By implementing a solar panel, sensors move from storing energy for a few months to just a few days, i.e., these just need to accumulate a portion of this energy to power the devices at night and days without much sunlight.

2.1.3 Safety and Security

Sensors that implement energy harvesting and wireless RF power transmission technologies enable fully-wireless approaches, such that these do not require to implement accessible wires or physical ports. Accordingly, these sensors can be hermetically sealed to separate the electrical circuitry and the system environment, bringing several benefits in terms of both security and safety.

On the one hand, such a closed system can only communicate through the wireless communication unit. This avoids any type of malicious attack that needs a physical or wired connection to capture internal signaling. On the other hand, the actual physical separation permits a sensor deployment in highly-inflammable environments, since any possible electrical spark will not ignite the flammable fluid.

2.1.4 Flexibility and Ubiquitousness

In addition to the benefits in terms of safety and security. Enabling fully wireless sensors also changes the way in that IoT is conceived since the communicating systems can be placed nearly anywhere. On the one hand, communicating systems can be deployed in locations that rendered unfeasible due to lack of accessibility to realize human maintenance. In addition to this, nodes do not need to be placed in known locations, as well as these can be dynamically displaced due to either environmental conditions or opportunism.

2.1.5 Economic and Environmental Impact

Energy harvesting and wireless RF power transmission permits the development of unattended wireless sensor networks that offer real-time monitoring of the nearby environment. This facilitates fast emergency control actions, plus an efficient use of the supplies, along with the associated cost reductions. Provided that this approach aims at suppressing the use of batteries and to perpetually recharge the sensors by means of the ambient energy, the IoT maintenance costs are assumed negligible and so its ecological footprint.

In addition to this, the ubiquitousness property of this approach will also open a whole set of new applications, broadening the existing IoT market. Accordingly, the economic impact of energy harvesting for IoT does not only lay on maintenance cost reductions, but also in the creation of new end applications.

2.2 Ambient Energy Sources

In an energy-harvesting-enabled wireless sensor node, the energy which is used to enable the sensing, processing and communications is fully obtained from its close environment by means of ambient energy harvesters [128]. In a real context, the energy that is used to power the sensors can be derived from a diverse set of physical phenomena, such as solar, thermal, acoustic, vibrational or RF energy. Unfortunately the available energy which can be harvested from each source of energy is usually limited and presents an unpredictable pattern in both temporal and spatial domains [128, 23]. For this, energy harvesting has become, on the one hand the key enabling technology for the IoT, whereas on the other hand, one of the largest constraints in capabilities and future performance of the networked systems.

In a general sense, it is found that some of the most important parame-

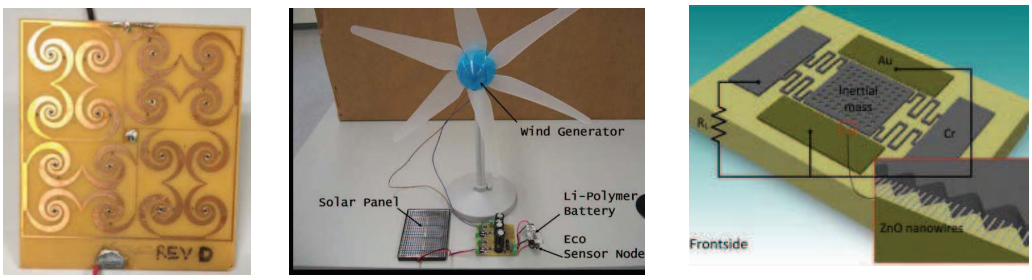

Figure 2.1: Examples of energy transducers: a rectenna [51](left), wind generator [107] (center) and a ZnO energy harvester [95](right).

ters to characterize a given source of energy are controllability, predictability, power availability or density and conversion efficiency of state-of-the-art transducers [128]. Controllability denotes the ability to modify the properties or power density of the source of energy. As an example, human movement stands as a controllable source of energy since. Predictability refers to the degree of prediction on the characteristics of the source of energy. For instance, solar energy is a predictable source of energy [46, 44]. Power availability or density is the expectable quantity of power that a sensor can harvest from the given source. This is size or area dependent, so it is usually expressed in terms of power over area units. Due to the unpredictable nature of the energy sources, the power density is illustrative and may vary over two orders of magnitude [128]. In Table 2.1 we show some results on the most relevant energy sources.

Table 2.1: Listing and characterization of the energy sources

Energy Source	Properties	Available Energy	Efficiency
Solar [132, 65, 8]	Uncontrollable, predictable	100 mW/cm^2	15% to 20%
Wind [142, 107, 81]	Uncontrollable, predictable	2 mW/cm^2	70%
Human Movement [124]	Controllable, predictable	1 mW to 1 W	7.5% to 40%
RF ambient Energy[15]	Uncontrollable, Unpredictable	1nW to 100 mW	40% to 50%
Vibration [116, 52]	Uncontrollable, Unpredictable	2 μW/cm^2	-

Fig. 2.1 shows examples of energy harvesting for RF ambient energy (left), wind (center) and Vibration (right). We describe next the most commonly considered sources of energy to power Internet of Things sensing systems and provide examples of implemented prototypes.

2.2.1 Solar Energy

Powering systems from solar energy is a widely considered approach, not only in the context of IoT, but in all nowadays applications. Even though, light is a time-dependent, time-varying source of power, it follows a predictable pattern [46]. This makes solar energy, one of the most stable and desired sources of energy for the considered sensors.

To scavenge the energy, sensors integrate photovoltaic cells that convert the incident light into an electrical current [73]. This generates an output DC current that can be leveraged to power the entire sensing system. the harvested power is in the order of 100 mW/cm^2. The pattern of the received power is uncontrollable and it is very affected by the geographical placement of the entire network and the particular location of the nodes. Hence, the actual received power varies over a large range. This shows a maximum power generation in outdoors locations with the photovoltaic cell facing the light source.

Solar energy shows a daily trend that is largely predictable. It has been shown that by considering accurate modeling and transmission policies, it is possible to achieve an energy neutral operation [73]. Thanks to this, solar energy has been widely considered to power WSN sensors as a mechanism to power and to re-charge the internal batteries. Among others, we find the following existing sensing platforms: [65, 64, 114, 73, 108].

2.2.2 Mechanical Vibration

Daily activities generate large amounts of residual energy that is expressed in the form of vibrations and mechanical movement. Plausible examples range from the subtle vibration of a floor or wall of a building when someone walks nearby, to severe excitation caused by industrial machinery. In all, mechanical vibrations are present in a wide variety of both frequency and amplitude ranges, which require application-specific hardware to optimize the energy scavenging [19].

To harvest energy from mechanical movement, an inertial mass can be used to generate electricity [5]. In particular, the acceleration of the suspended inertial mass induces an electrical current that can be rectified and stored in a capacitor. For this three different mechanisms, namely, piezoelectric [5], electrostatic [120] and electromagnetic, stand as the feasible approaches.

The piezoelectric energy harvesting bases its operation principle on given materials that generate an electrical current when these are deformed [19]. This property has been leveraged by numerous researchers to implement energy harvesting for a wide variety of applications [10, 5, 32, 85]. Electrostatic energy harvesting consists of generating energy by moving the plates of a charged capacitor. When the plates are moved, the variations on the electrostatic force generates a voltage signal, which can be harvested [10, 120, 90]. Finally, electromagnetic energy harvesting is based on the Ampere law to generate electrical current by fluctuating the magnetic field around a coil [10].

2.2.3 Thermal Energy

Thermal energy can be also harvested through the action of thermoelectric generators, by leveraging the Seebeck effect [127]. This effect generates an electrical voltage that depends on the temperature difference at the junction of two dissimilar metals. In practice, this is generally implemented with a Peltier plate, where one side is connected to a heat source, whereas the remainder to a heat sink. However, the thermal to electrical energy conversion shows very poor efficiency, that is in the order of 5% [127]. Thermoelectric generators show an interesting approach to reuse the extra heat generated by human machinery, hence improving the energy efficiency of the system if considered as a whole [19].

2.2.4 Wireless RF Energy

Electromagnetic waves are widely employed as a method to broadcast and to propagate information. These are transmitted by base stations and aim at covering large geographical areas. Provided that the RF spectrum is a limited and scarce resource, frequency bands allocate a large amount of power, where sensors can harvest energy from.

To harvest the RF power, sensors integrate antennas. Antennas generate a voltage signal at the frequency of the received RF wave and its power is proportional to the power density of the RF wave. However, given that RF power can be neither stored nor used to supply the remaining sub-system units, the RF signal is down-converted by means of a rectifying stage [33] and, sometimes, a DC-DC converter to improve the conversion efficiency [56]. The design of antennas for wireless RF energy harvesting does not pose additional challenges to those for signal reception. Alternatively, the concept of rectennas has also been well accepted in the research community [113]. These circuits refer to a combination of an antenna and rectifying, built for energy efficiency maximization.

The amount of harvestable power and size of the antennas depend in a great manner on the available RF power in the nearby spectrum. Accordingly, the size of an antenna is proportional to the wavelength of the RF wave, such that higher frequencies require smaller antennas and vice-versa. The received power, however, depends on the transmitter-receiver pair distance and frequency. The attenuation is proportional to the square of the distance and the frequency. It has been experimentally shown that it is possible to harvest up to 60 μW at a distance of 4.1 km in an urban environment [122].

Alternatively, wireless RF energy has also attracted the research community as a method to supply power on-demand on a wireless manner. This approach has given birth to wireless RF power transmission, which is discussed in Sec. 2.4

2.3 Energy Harvesting

In the recent years, several works ranging from the energy harvester circuit design to the network analysis has driven the research in the field of energy harvesting enabled WSN and IoT. Along these works, different type of energy sources have been characterized, energy scavengers, power electronics circuits and tools for low-power applications have been provided and a dense study on communications has been carried out [7, 84, 128, 133, 138].

These studies have remarkably shown the large degree of analytical complexity of energy harvesting systems. From a descriptive viewpoint, a generic system requires handling random processes at both input (harvested energy) and output (communications), while defining an energy state, also referred as residual energy, that varies in time in a non-predictable manner. Accordingly, energy modeling [102], optimal scheduling [7], dimensioning of the energy buffer [73] and design of the protocol stack have been some of the most active challenges that the research community has set to tackle.

Overall, energy harvesting conditions the design of the WSN at many different levels. This section overviews the design implications accross the different layers.

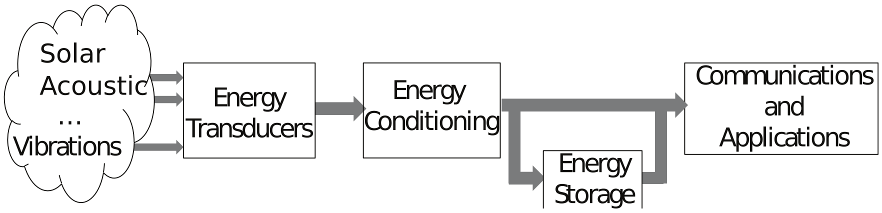

Figure 2.2: Depiction of the energy path.

2.3.1 Circuit Level

At the circuit level, the harvested energy is acquired through the action of the transducers. This is temporarily stored in an energy buffer. Finally, the energy is distributed to the different sub-system units to enable their normal operation. This flow is referred as the energy path and it is shown in Fig. 2.2.

An energy transducer is defined as a device which is capable of converting the energy of certain physical magnitude into electrical energy. i.e., the energy which is available in the close environment of the sensor is harvested through energy transducers and converted into electrical energy. In accordance with the energy sources, there also exist several types of energy transducers, depending on the nature of the energy source, such as MEMS and NEMS for vibrational and mechanical energy harvesting, which can be either resonant [116] or non-linear [52], antennas and rectennas for RF energy harvesting [51] or solar cells [65].

Energy transducers are very sensitive to size downscaling, since a modification in size or area of the transducer may affect critical parameters, such as oscillation frequency. As an example, in RF energy harvesting, the size of the rectenna is directly related to the targeted RF wavelength. i.e., the natural frequency for energy harvesting dramatically increases as the size downscaling in the rectenna is performed. In this context, nanotechnology-based novel transducers aim to provide similar properties of classical energy transducers at a much lower size. As an example, a graphene-based nano-antenna allows a reduction in size of two orders of magnitude (up to 100 times smaller), in comparison to metallic antennas, while still operating at the same frequency [69]. Accordingly, combining multiple energy harvesters to reduce the overall area, while meeting the user-defined requirements is set as a major research challenge that the community has set to tackle [22, 31]

The subsequent part of the energy path aims at conditioning the harvesting energy to the sensor requirements. As a result, the energy conditioning block provides the matching between the energy transducers to the sensor node [30, 8, 133]. As an example, in case of harvesting AC energy, this needs to be downconverted to DC current by means of a rectifying circuit [100].

By following the energy path, the harvested energy is required to be temporarily stored in an energy buffer, until this is used by the communication or processing unit of the sensor node. This block results of vital importance for the performance of the sensor node due to the fact that ambient energy sources provide not only low-power densities, but also they present a large sparsity and time-variant character [7].

The energy storage is usually composed of a battery or a supercapacitor [128]. Unfortunately, there is a huge compromise among both technologies. Particularly, batteries usually provide larger energy densities than capacitors. On the other hand, capacitors can handle faster energy fluctuations and have larger recharging cycles [132, 77, 112]. As a result, the strong compromise among technologies makes very challenging for the electronics designer to decide whether to use either one, another or both. Table 2.2 shows typical values for batteries.

Table 2.2: Comparison of battery technologies [132, 128]

Technology	Energy Density (MJ/kg)	Recharging cycles
Sealed Lead Acid	0.11-0.14	500-800
Ni-cadmium	0.14-0.22	1500
NiMH	0.11-0.29	1000
Li-ion	0.11-0.29	1200

2.3.2 Energy State Modeling

The existing state-of-the-art joint models, which are based on Markov queues, can be roughly classified into three types. In the first type the basic unit is the energy packet and -unlike classical communications queues- empty queues of energy packets entail an interruption of the normal operation of the sensor nodes. In such models the energy harvesters generate arrivals of energy packets that in turn, are stored in the energy buffer (representing a battery or a supercapacitor). The communication unit is modeled as a server which processes the energy packets where the service time is associated to the generation of communications events[136, 70, 148]. The second type of models proposes the interconnection of two different Markov chains, namely a main queue for communications packets and a secondary queue for energy harvesting resources. Such type of models consider that a data packet can be effectively transmitted when it has been processed by the main queue and the queue of energy-packets is not empty [7, 102, 115]. And finally, the third type are based on state-dependent Markov chains where each state represents a combination of the amount of energy,data packets available in their respective buffers [88, 123].

Alternatively, existing joint models for solar energy harvesting account for daily temporal variations of the ambient energy. Due to the fact that solar energy provides a significantly larger amount of energy, and due to the fact that sensor nodes must store enough energy for several hours, these models are very source-specific, and therefore not general purpose [45, 73, 130, 83].

Overall, existing joint energy/information models suffer from a remarkable degree of complexity, at the same time extending them to account for multi-source energy harvesting systems is challenging since the energy harvesters are not considered as individual entities. Furthermore, they are not typically equivalent to classical communication models and as such, harder to solve. Developing a new type of model that it is simple, accurate and that naturally accounts for the multi-energy harvesting environment is set as a pending challenge.

2.3.3 Physical Layer Design

The physical layer is in charge of enabling a physical medium to transmit information. This layer aims at determining optimal power allocation and transmission policies to transmit in the best conditions [83, 7, 45, 58], as well as energy efficient modulations and transmission schemes to survive the large interferences of the transmitted power [96]. As one of the main research problems in this context we find the field of information theory. where, the channel capacity of energy harvesting enabled WSN and IoT have been extensely addressed [115, 104, 103, 134].

2.3.4 MAC Layer Design

It is widely accepted that communication in WSN requires more energy resources than computation. For this, reducing unwanted collisions and retransmissions of data packets becomes one of the challenges that the research community has mostly set to tackle. MAC protocols for energy harvesting WSN are thought as opposed to conventional energy-constrained MAC protocols. Provided that the energy state of the sensor is constantly changing, sensors aim at efficiently using the energy resources of the sensor, rather than employing energy-saving approaches [76, 61].

There exist a wide variety of MAC protocols designed for energy harvesting. These can be categorized in three main groups. First, polling-based protocols such as PP-MAC, EH-MAC and MTTP [76, 42]. Second, random access protocols, which, among others, considers ALOHA and CSMA-based protocols [61, 135]. Finally, scheduled protocols based on TDMA approaches [61, 135].

2.3.5 Energy Harvesting Wireless Sensor Networks

Energy harvesting changes the way in which networks are designed and considered. Non-energy harvesting powered IoT are constrained by the capacity of their batteries, such that nodes aim at optimizing the communication and network operation following an energy saving approach. On the contrary, energy harvesting defines energy as an unlimited resource, with scarce and non uniform availability, whereas the storage of energy is far limited. In this novel scenario, saving energy to extend the sensor lifetime is usually not the best approach, since it is likely to entirely fulfill the energy buffer. Accordingly, energy harvesting powered sensors need to follow energy efficient policies to maximize the use of the energy.

The study of WSN powered by energy harvesting starts from a simple transmitter-receiver pair [17]. From the networking viewpoint, studying the access of energy in large scales networks is posed as a major challenge. Among the different scenarios, mobile ad-hoc networks (MANETs) and cellular networks have attracted the interest of many research groups [59, 60].

2.4 Wireless RF Power Transmission

Wireless RF power transmission is emerging as a promising approach to enable battery-less wireless sensor networks (WSNs) [113, 144, 79, 145]. This technique aims to leverage RF energy harvesting [128, 141], which will allow controlled powering of nodes that may have insufficient residual energy in their batteries, or are unable to scavenge energy from the ambient environment (say, through solar, wind, vibration) at desired rates.

2.4.1 Circuit Design

The main circuits, which are required to implement an energy harvester for wireless RF power tranmission, are the antenna and a rectifying circuit, which converts the RF power into a DC current [138]. In case that both components are jointly integrated, this is referred as rectenna [51, 113]. However, employing separated circuits has been lately considered as an interesting approach to permit a dual operation of the considered antenna [82]. Hence acting for both communication and power transmission actions.

The non-linear behavior of semiconductor devices results in the dependency of the input impedance with the input power, such that the antenna and energy harvester impedances match only for a certain input power. The impedance matching makes two distinguished regions in any real implementation [33]: Increasing efficiency for low input powers and decreasing efficiency for high input powers. In region I, transmitting power in a time-varying manner leads to higher amounts of harvested energy [14]. On the contrary, in region II the power conversion efficiency at the high power range decreases with the input power [33], and a low peak-to-average received power ratio improves the efficiency of the energy harvester.

High-efficient energy harvesters integrate two separated and generic stages for energy optimization [56]. First, a rectifying circuit is employed that can convert with very high efficiency the harvested power. Then, a DC-DC boost converter operating in discontinuous conduction mode (DCM) is considered to transfer the accumulated energy in a temporal capacitor towards the energy storage unit (i.e., a super-capacitor or battery). The control unit handles the operation of this converter.

The aim of this dual-stage design is to optimize the transfer of energy by accurately matching the input impedance of the rectifying stage, which depends on its output load [100]. In particular, when connecting a rectifying stage for energy harvesting applications to an energy buffer, it shows a time-variable conversion efficiency, showing poor performance when the output capacitor voltage is either too low or too high [56]. For this, a small capacitor is connected to the output of the rectifier, which permits to rapidly skip the low-voltage operation regime (i.e., below a given voltage level). When its output voltage surpasses a given threshold the stored energy is high efficiently transferred to the output energy buffer through a DC-DC boost converter, leaving the voltage at the temporal capacitor at a low voltage (the duration time of this action is referred as *on-time*). As such, the voltage of the temporal capacitor approximates a saw-tooth waveform [34], and the output current of the energy harvester is in form of short time-scale spikes. Accordingly, the saw-tooth waveform period inversely depends on the input power.

2.4.2 Transmission of Energy

Given the relatively short charging range of one energy transmitter (ET), either mobile ETs or multiple ETs are required to cover large deployment areas [39, 40, 97] in WSN. The presence of multiple ETs reduces the average propagation distance to the energy harvesting sensors, and thus decreases the attenuation level of the energy waves and improve the RF power harvesting rates [55].

In multi-ET deployment scenarios, RF waves may interfere with each other when they are transmitted in the same medium. These interferences can be either constructive (i.e., the received power is larger than the average) or destructive (i.e., the received power is very low, or even zero) as shown in [97, 117], requiring ETs to implement energy multiplexing techniques for wireless RF power transimssion [144]. It can be observed that the constructive and destructive combination of RF waves generate very large peaks and drops of power in a non-controllable spatial-dependent manner.

Existing energy multiplexing approaches for wireless RF power transmission can be classified in two distinguishable groups. On the one hand, orthogonal methods can be utilized to mitigate interferences between transmissions of energy, therefore providing separated access channels for each transmission of energy. In this group we find a large variety of multiple access methods that were proposed for communications and can be implemented for wireless RF power transmission as energy multiplexing methods, such as TDMA, FDMA, OFDMA [99], FHSS and DSSS [35]. This approach requires lightweight synchronization among ETs to guarantee non-interfering power transmissions [35]. Also, cooperative communication methods for many-to-single and many-to-many communication can also be considered [78]. On the other hand, distributed beamforming methods [94, 80] aim at constructively combining the RF waves at the recipient end to maximize the power transfer in a many (ETs)-to-many (sensors) configuration [144, 97, 80]. In this group, massive MIMO stands as the best alternative to optimize the power transfer. This was first showed in a two-user case [109] and later extended to a generic k-user [110]. However, this approach comes at the non-negligible cost of increasing hardware complexity by necessitating k antennas per ET, with k the number of deployed sensors, and requiring a node to ET communication link for channel state information reporting [110].

2.4.3 Energy and Communications

Using the RF spectrum for both energy and data transfer, however, may seriously affect network operations and performance, and require sophisticated hardware and devices that many systems cannot afford. For instance, transmitting energy and data on different frequencies [101] would require multiple or broadband access capabilities, since the frequency gap between energy and data communications cannot be very small [96]. Alternatively, when both energy and data share a single band, specialized MAC protocols are required [97]. In both cases, devices should feature two separate RF front-ends, for decoding the information and converting RF energy into DC [111]. Therefore, devising methods for energy provisioning without affecting data communications appears to be the challenge to tackle [48].

Simultaneous wireless information and power transfer (SWIPT) and full duplex energy harvesting have been presented in [82, 72]. These technologies aim to deliver information over a wireless medium during the simultaneous transmission of energy. However, SWIPT enables the transmission of data and energy from the same network device, thus enabling downlink communications, whereas full-duplex energy harvesting aims at receiving energy as the device transmits it, thus targeting uplink communications. In these fields, significant work has been recently performed, which includes considering MIMO-based solutions [147] or simultaneous relay of energy and data [20]. In particular, a model for integrated data and energy transmission using SWIPT has been presented in [149].

Simultaneous transmission of energy and data is also provided by other technologies. For instance, RFID technologies inherently implement simultaneous transmission of energy and data, being based on backscatter communications [140]. In line with this approach, backscatter communications have recently been presented and experimentally demonstrated for wireless RF [84]. This approach leverages ambient RF waves produced by a third entity that are passively reflected from the transmitting to the receiving node. To reflect the RF wave and to modulate information, the impedance of the antenna is being constantly modified at the transmitter (i.e., short-circuiting and open circuiting the antenna to modify its reflection properties and to transmit logic '1's and '0's). Ambient backscatter enables ultra low power communications over an active transmission of energy. However, the transmitting node cannot allocate power as it reflects a portion of the power that it receives, whereas the allocated power in our approach is a design parameter. On the receiver side, no integrated data and energy receiver has been implemented, so the receiving sensor has to switch between activities, thus requiring synchronized MAC protocols to detect active data transmission.