FINAL YEAR PROJECT

---

# IMPACT OF MOBILE TRANSMITTER SOURCES ON RADIO FREQUENCY ENERGY HARVESTING

---

*Author:*
Antonio HERNANDEZ COARASA

*Advisor:*
Dr. Kaushik CHOWDHURY

ESCOLA TECNICA SUPERIOR D'ENGINYERS DE TELECOMUNICACIO DE BARCELONA

**Acknowledgements**

I would like to dedicate this work to all the people who have made this project possible through their dedication during all the year here in Boston. First of all to Professor Kaushik R. Chowdhury for offering me the opportunity of finishing my Engineering studies in USA giving me a place in his lab in Northeastern University. Thank for all the time destined to this work and specially to the stressing days before the paper deadline. I hope we will have time to meet again and return this help.

Also a special gratitude to all the people conforming the 227 Egan Research Building laboratory for all the hours shared there. A Prusayon for all the knowledge provided and the different discussions about the topic, but also to Ufuk, Rahman, Yousof, Leandro and Farimah for all the time supporting me and helping me to avoid stress when deadlines where close.

Also a gratitude to all the faculties in UPC who made all this experience possible giving me a opportunity to expand my networking with the Northeastern University students and Professors. Specially to Eduard Alarcon for his help at the time of the destiny decision.

All the previous people have offered me an immeasurable support to develop this research project but living a new live in a new country with new cultures, new food, new habits in general would have never been possible with those other persons who manage to offer my a life out of this lab. Thanks a lot for all to Edu, Hasier, Marc, Leonie, Alizee and Deborah for all the time shared during those months from beginning to end. Also to Ramon, Dolores and Marc for the new fresh air brought to me in February and all the support obtained. And also to all the other people, specially the European sector, who I had the honor of meeting during this unforgettable year in Boston.

To all the friends I have met in Telecos, BEST and Penyafort for all this marvelous years in Barcelona which have finished here with this project. To Ventura, who not only has been in my side on all this places but also guided me to facilitate my arrival in Boston.

Also special and very important greetings to those people who, through the new technologies have been supporting me day by day even coming to visit me to Boston. Specially to Alba.

Finalmente, pero no por ello menos importante, un enorme agradecimiento a toda mi familia por el apoyo enviado desde casa, y en especial a mis padres Antonio y la Manca de Lepanto y a mi hermana Blanca por todo, por creer en mi, por apoyarme en todo y por sentirse tan orgullosos.

**Abstract**

Wireless energy harvesting sensors networks constitute a new paradigm, where the motes deployed in the field are no longer constrained by the limited battery resource, but are able to recharge themselves through directed electromagnetic energy transfer. The energy sources, whom we call *actors*, are mobile and move along pre-decided patterns while radiating an appropriate level of energy, sufficient enough to charge the sensors at an acceptable rate.

This is the first work that investigates the impact of energy transfer, especially concerning the energy gain in the sensors, the energy spent by the *actors*, and the overall lifetime in the resulting mobile sensor-*actor* networks. We propose two event-specific mobility models, where the events occur at the centers of a Voronoi tessellation, and the *actors* move along either (i) the edges of the Voronoi cells, or (ii) directly from one event center to another. We undertake a comprehensive simulation based study using traces obtained from our experimental energy harvesting circuits powering Mica2 motes.

Our results reveal several non-intuitive outcomes, and provide guidelines on which mobility model may be adopted based on the distribution of the events and *actors*.

---

Las Redes inalámbricas de sensores dotadas de sistemas de recolectamiento de energía (Wireless energy harvesting sensors networks en inglés) constituyen un nuevo paradigma donde los motes (elementos inalámbricos dotados de un sistema de comunicación por radio y sensores) esparcidos por el terreno ya no estan limitados por una fuente energética finita sino que son capaces de recargarse ellos mismos mediante una transferencia de energía electrómagnetica. Dichas fuentes de energía, llamadas *actores* son móviles y se desplazan mediante una serie de vías predeterminadas mientras radían ondas electromagnéticas a un cierto nivel de potencia apropiado suficiente para producir un proceso de carga suficiente en los sensores.

Este es el primer proyecto de investigación enfocado al impacto de la transefencia de energía, especialmente refiriendose a la ganancia de energía en los sensores, la energía consumida por los actores y el cómputo de la vida total útil de la red resultante. Se proponen dos modelos de movilidad especificos para un grupo de eventos donde estos ocurren en el centro de cada una de las celdas de una teselación Voronoi y donde los actores se mueven (i) a través de los bordes de las celdas o (ii) directamente de la localización de un evento al siguiente. Se realiza un amplio estudio basado en una simulación usando

los resultados obtenidos de los circuitos de recolectamiento de energía anteriormente creados para los modelos Mica2.

Se revelan varios resultados no intuitivos y se proprcionan guías sobre cuáles deberían ser los modelos de movilidad adaptados en cada red dependiendo en la distribución de los eventos y los actores.

# Contents

**Contents** i

**List of Figures** iii

**List of Tables** v

**1 Introduction** 1

1.1 Contribution of our project . . . 3

**2 Wireless Sensors and *Actors* Networks (WSANs)** 6

2.1 WSAN Characteristics . . . 7

2.2 WSAN Architecture . . . 11

2.2.1 MOTE components . . . 13

2.3 WSAN Applications . . . 15

2.4 Issues of battery powering in WSAN . . . 16

**3 Energy Harvesting** 19

3.1 Energy Harvesting architecture . . . 19

3.2 Energy Harvesting sources . . . 21

3.2.1 Motivation to use Radio Frequency Energy Harvesting . . . 23

3.3 Energy Harvesting in WSAN . . . 25

**4 Simulation Setup** 29

4.1 Sensors and events generation . . . 29

4.2 Voronoi Tessellation . . . 30

4.3 Moving models . . . 31

4.3.1 Center to center moving model (CM) . . . 32
4.3.2 Around edges moving model (EM) . . . 32
4.4 *Actors* deployment . . . 33
4.4.1 Deployment EM . . . 33
4.4.2 Deployment CM . . . 34
4.5 Moving *actors* and energy propagation . . . 35
4.6 Data management . . . 36

**5 Performance Evaluation and Observations 40**
5.1 Minimum received power at EP . . . 41
5.2 Frequency of transmission by *actors* . . . 43
5.3 Number of *actors* . . . 46
5.4 Number of Event Points . . . 47
5.5 Probability of consuming by sensors . . . 49
5.6 Area scenario . . . 50

**6 Empirical measurements of Radio Frequency Energy Harvesting 54**
6.1 Results discussion . . . 57

**7 Open Issues and Conclusions 61**

**A Acronyms 64**

**Bibliography 65**

# List of Figures

1.1 RF harvesting circuits . . . . . 4

2.1 Duty cycles chronographs for WSAN . . . . . 10
2.2 Network architectures: a) chain, b) tree, c) token ring, d) star, e) mesh . . . . . 11
2.3 Network components . . . . . 13
2.4 Mica2 and MTS310 sensor board elements . . . . . 14
2.5 Application categories of WSAN . . . . . 15

3.1 Voltage multiplier circuit schematic . . . . . 21
3.2 Energy Harvesting sources [7] . . . . . 22

4.1 Voronoi tessellation . . . . . 31
4.2 Moving models schemes. *Actors* (squares), Event points (+), Sensors (o) and boundaries of the Voronoi cells (grey lines) . . . . . 31
4.3 *Actor* deployment for CM . . . . . 34
4.4 *Actor* deployment for EM . . . . . 35
4.5 Energy Harvesting Efficiency for 915 MHz circuit . . . . . 37

5.1 Energy results when the minimum required power at the EP varies . . . . . 41
5.2 Lifetime when the minimum required power at the EP varies . . . . . 42
5.3 Energy results when the minimum required power at the EP varies when the EH frequency varies . . . . . 44
5.4 Lifetime when the EH frequency varies . . . . . 45
5.5 Energy results when the minimum required power at the EP varies for different frequencies when the minimum required power at the EP (X axis) varies . . . . . 46

5.6 Energy results when the minimum required power at the EP varies when the number of *actors* varies . . . 47
5.7 Lifetime when the number of *actors* varies . . . 48
5.8 Energy results when the minimum required power at the EP varies when varying the number of Event Points (b) . . . 49
5.9 Lifetime when the number of Event points varies . . . 50
5.10 Energy results when the minimum required power at the EP varies when varying probability of consuming by sensors (b) . . . 51
5.11 Lifetime when the seconds between sensing varies . . . 52
5.12 Energy results when the minimum required power at the EP varies when the scenario area varies . . . 53
5.13 Lifetime when the area of the scenario varies . . . 53

6.1 One ray model . . . 55
6.2 Two ray model . . . 56
6.3 Voltage obtained with different antennas and emitter at a height of 71.5 cm . . . 58
6.4 Voltage obtained with omnidirectional antenna and emitter at different heights . . . 59
6.5 Variations of received voltage with distance in different locations of a same scenario (closed corridor) . . . 60

# List of Tables

3.1 Prediction and Control of Energy Harvesting Sources . . . . . 24
3.2 Different power outputs for Energy Harvesting systems [19, 20] . . . . . 26

4.1 Parameters for the simulations . . . . . 38

# Chapter 1

# Introduction

Since Marconi's original demonstration of the radio in 1897, researchers and practitioners have persistently pushed the state of the art in telecommunications. This transition from the "wired" to the "wireless" domain brought about a radical change, leaving behind the limitations of physical media (such as copper wires, and later, fiber optic cables) and bringing with this transformation, new challenges. As an example, energy conservation, which was not a key consideration earlier in the wired world, simply because of fixed equipment with dedicated power connectivity, suddenly assumed an important role. Wirelessly connected devices were no longer tethered, and then a local storage of energy in the form of batteries was required. On the other hand, the wired world gave precedence to problems of security (through cryptography and steganography), speed of data transfer (through different communication and message sharing protocols, working in series or parallel, intelligent packet size formulation, among others) and reliable data delivery (through end to end that allow the connection to recover from errors, congestions, among others).

The replication of the widespread nature of wired network connectivity in the wireless domain has brought about many exciting challenges. There are now solutions that connect personal devices, such as computer peripherals or body area networks; small office or home networks through wireless LANs, large-area networks served by cellular operators, among others. Wireless communication has extended to underwater scenarios through a combination of radio frequency (RF) and acoustic wave propagation; and extra-terrestrial or space environments through delay tolerant, low data rate links.

In many of the above scenarios, a functioning network is only possible owing to the absence of wires. A seminal result that laid the foundation of sending information by manipulating electromagnetic fields, attributed to James Clerk Maxwell at the end of XIX century, started this explosion of wireless

applications that we see today. In the modern world around us, we carry smart phones, live in smart, sensor embedded spaces, and have appliances that self-monitor and report their power usages, all relying on some form of wireless communication. Needless to say, as our reliance on them keeps increasing, so do concerns of their correct operation and pervasive availability.

The wireless sensors are becoming more commonplace today, with advancements in fabrication technology driving down per unit costs. These sensors are often deployed randomly, possibly dropped from an aircraft, or simply placed at vantage points within the area being monitored. Once activated in the field, it is often difficult, if not impossible to retrieve these sensors and replace their on-board batteries. Besides, such networks are often heterogeneous, with some nodes and components requiring different levels of energy consumption. Hence, to ensure long-term operation of these sensors, there has been considerable effort towards enhancing the energy efficiency of the network.

This awareness of energy has pervaded through the entire protocol stack, beginning from using power saving modulation schemes, encouraging low transmission powers, forcing sleep-awake duty cycles, implementing high density batteries, compressing data before transmission, load sharing during the data forwarding process, among others. While these approaches have been undoubtedly effective, they merely help in alleviating the energy shortage partially. There are often limits to the energy savings that is obtained from a combination of these techniques which are unfeasible to achieve by the actual battery systems.

Many issues concerning the use of battery powering, from the low accessibility of the nodes for battery replacement, the low capacity of actual battery technologies compared to the wireless network expected lifetime or the hazard of the battery products towards the ecosystems where networks can be disposed, have lead investigators to study new ways to obtain energy from others sources instead of batteries, which motivates the main idea and direction of this thesis.

We look at the larger problem of reclaiming energy from ambient sources, or so called ”Energy Harvesting” which can complement any of the above energy saving ideas, further improving the lifetime. In an ideal world, we would like energy neutral operation, i.e., the network is able to recover whatever energy is lost in its operation. Practical limitations in terms of the amount of harvestable energy that is available at the node locations, and the efficiency of conversion of this ambient energy into useful electrical energy affect the actual energy store that is available during the network operation.

There are various kinds of energy harvesting systems, relying on solar power, wind, body processes, and mechanical vibrations, among others. However, these sources are either intermittently available

or are severely weather dependent. Instead, we explore a new paradigm in this thesis, concerned with wireless radio frequency Energy Harvesting.

Our work is mainly focused on mobile networks where the energy supplier is capable of motion and has a large or inextinguishable energy store. We call these suppliers as "*actors*". The recipients are energy-constrained sensors that are deployed in the field. The resulting sensor-actor network is able to continuously operate using periodic energy replenishments, whenever the actor is physically close to the sensor and is able to transmit energy wirelessly to it through directed electromagnetic waves. The main contribution of the thesis is concerned with exploring the scenarios in which such transfer of energy is effective, the impact of mobility, the density of actors and sensors, among others.

The organization of this thesis is as follows: In section 1.1 we can find the actual state of the art and a brief introduction about our contribution, while a deeper explanation on both Wireless Sensors and *Actors* Network and Energy Harvesting concepts can be found in Chapters 2 and 3 respectively providing the reader a knowledge background sufficient to comprehend and assimilate properly the research developed and the results obtained.

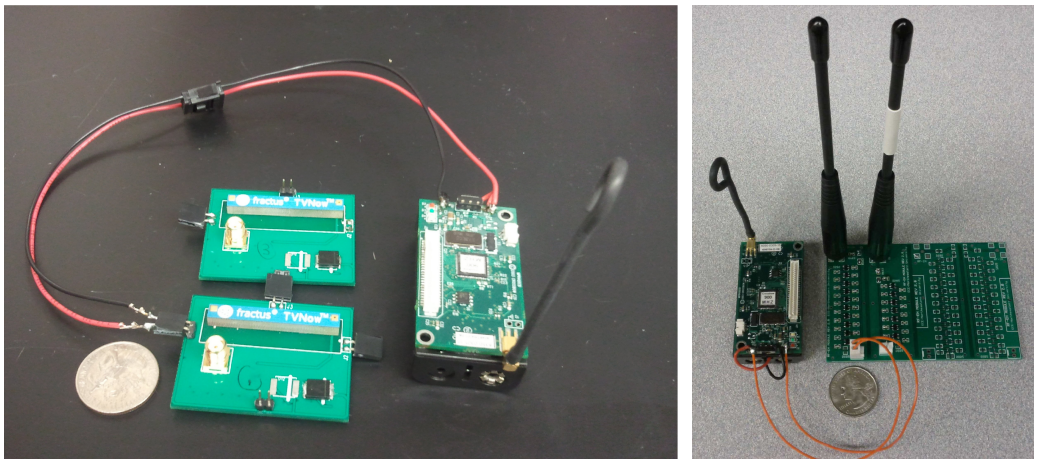
Afterwards an accurate description of the Simulation Setup can be found in Chapter 4 followed by an exposition of the results obtained in Chapter 5 and the final Conclusion and introduction of open issues in Chapter 7.

## 1.1 Contribution of our project

This projects gets inspired by the new paradigm set by Energy Harvesting from RF waves [16], that goes beyond the commonly assumed forms of energy obtained from wind [23] and the incident sunlight [9] providing new ways to sustain a Wireless Sensors and *Actors* Network through Energy Harvesting. This technology viability has been demonstrated through different commercial and research prototypes [8, 10, 15, 17], apart from our own efforts in [14].

While other projects have already evaluated how to apply RF Energy Harvesting to WSAN, this project leads the RF Energy Harvesting implementation research through the application of *actors* that react to events and address them, which has been explored in [12] and similarly for moving data sinks in [1, 11]. Those *actors*, are a energy-rich source, which move around in the network. It radiates energy through RF transmissions, which is captured and converted by the on-field sensors connected to energy harvesting circuits. Two such harvesting circuit designs interfaced with a MICA2 mote for the 600 MHz

(licensed band) and 900 MHz (unlicensed ISM band) are shown in Figure 1.1a and 1.1b. This work has already exposed in a publication [3] which is under submission.



(a) 600 MHz (b) 900 MHz

Figure 1.1: RF harvesting circuits

These *actors* may move under a variety of mobility patterns, common examples being Brownian model, Random way-point model, Random walk model, among others. However, for the purpose of this paper, we assume that the *actors* move along certain specific paths, based on where the events actually occur. This allows focused charging of the sensors at those event locations. We make the use of Voronoi tessellations in this work, where the area is split into regions, called as Voronoi cells [5].

They also radiate power at different levels depending upon how close or far they are from the event. We assume that the sensors around the event location are maximally impacted by the event, i.e., they have a higher duty cycle of sensing, reporting the readings, compressing measurements based on correlation and aggregating the data from neighbor. These activities not only involve higher transmission costs, but also higher expenditure from on-board computations. Thus, the primary aim of the *actor* is to ensure that the nodes around the event are kept alive, and any variation in the radiated power is always bounded by the minimum RF power level incident at these event locations.

Moreover, as the *actors* move, they themselves consume energy, and path planning needs to be carefully considered in the design. In this study, we look at an in-depth evaluation of multiple additional factors including the effect of sensor duty cycles, amount of *actors*, number of event locations, the minimum required power to charge for a given sensor, the density of sensor deployment, and the frequency

in which the radiation occurs.

In summary, the main contributions of this study are:

- We explore the trade-off between (i) whether to transmit at high power from a distance, or (ii) move closer to the event area to decrease the required power to transmit, with the resulting impact on the energy loss due to motion.
- We earlier designed and interfaced two prototypes that harvest energy from licensed in the 600 MHz, and the easily accessible ISM bands (Figure 1.1) [14]. Here, we study if the energy transfer efficiency in the licensed frequencies justify the additional licensed user avoidance overhead.
- We identify which of the environmental factors (e.g., node density, event density, *actor* density, mobility pattern, transmission power variation) are dominant in ensuring long network lifetime.

The remainder of this project is organized as follows. In Chapter 4 we describe the whole set up of our studied scenario, from the deployment of the sensors to the acquired data processing. In Chapter 5 we evaluate extensively the performance from the data acquired from the simulation and in Chapter 6 measurements of voltage levels obtained by our Energy Harvesting systems are analyzed to evaluate the accuracy of different wave attenuation models. Finally, we draw conclusions in Chapter 7.

# Chapter 2

# Wireless Sensors and *Actors* Networks (WSANs)

Wireless Sensors and *Actors* Networks (usually referred by its acronym WSAN, or WSN when *actors* are not used) enshrine a certain sensors based network which is doted of the required infrastructure to perform a wireless communication instead of a cooper of fiber optic connection. From [18] we can define this sort of network as:

> "A Wireless Sensors Networks (WSN) consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. WSN contains a large number of nodes with a limited energy supply. A wireless sensor network consists of nodes that can communicate with each other via wireless links. Sensors are be remotely deployed in large numbers and operates autonomously in unattended environments. One way to support efficient communication between sensors is to organize the network into several groups, called clusters, with each cluster electing one node as the head of cluster To support scalability, nodes are often grouped into disjoint and mostly non-overlapping clusters." [18]

Through the incorporation of high-processing level network elements, called *actors*, capable of performing more complex and efficient tasks, the WSAN are conformed. in our case transmitting Radio Frequency waves while moving through the scenario. From now on we will always refer to WSAN independently of the existence of absence of *actors* in order to simply the descriptions in the next subsections. The common elements are always the sensors, although the mote (from reMOTE) term is sometimes used

to generalize more and use the sensors term only for those which are really sensing the scenario and not just working on packet transmission.

The main difference between a WSN and a WSAN is, as exposed before, the existence of a special element, called *actors*, of higher processing power, which provide special functions, in our case transmitting Radio Frequency waves while moving through the scenario. From now on we will always refer to WSAN independently of the existence of absence of *actors* in order to simply the descriptions in the next subsections. The common elements are always the sensors, although the mote (from reMOTE) term is sometimes used to generalize more and use the sensors term only for those which are really sensing the scenario and not just working on packet transmission.

## 2.1 WSAN Characteristics

One WSAN, as seen on the previous definition, is sustained by a whole set of characteristics which are explained here:

- Dynamic connections topology: Due to its high dynamism, as it forms an ad-hoc network (new elements can be incorporated or removed at any moment), it has to be programmed to change the connections through two random points at any moment depending on the state of the rest of the motes. It allows to ensure a larger network lifetime even when some motes discharge or stop working properly and also to introduce new elements at any time.

- Detection of communication failures: As the communication media is shared by all the terminals forming the network, an efficient system controlling the failures is necessary, setting a protocol good enough to deal with packet crashing, possible interferences, attenuation, death motes for rerouting, ...

- Heterogeneity of nodes: A dynamic network has to be prepared to deal with different kind of elements and communication systems providing the network a easier evolution way with the changes it suffers providing a global communication protocol. This way the communication among different motes, motes and sinks and other possible elements as *actors* will be the same, facilitating the performance of the whole network.

- Scalability: A well structured WSAN has to be prepared to be scaled without reducing its functionality even though some clustering algorithms might be necessary to keep the efficiency and

low-computational cost required. We have to consider the network can be formed by a few units up to thousands of elements, implying variation also in distance through nodes and thus in the power required. As the networks are dynamic those configurations have to be also dynamic to interact properly under any network alteration.

- Ability to withstand harsh environmental conditions: It is necessary to get the network elements prepared to all kinds of harsh situations as they can be deployed in different scenarios suffering humidity, extreme temperatures, shocks, different pressures, ...

- Ease of use: An easy deployment and set up process is necessary to facilitate the use of this kind of networks as they are very scalable and the configuration cost grows up very fast with the size of the network.

- Unattended operation: Because of the large size the networks can achieve, monitoring the whole network is computational unfeasible, having to provide the motes, inside of their low-computational constraints, of some tools to maintain themselves and, if necessary, set some special motes, as can be some *actors*, to control the different clusters inside a network.

- Low Power consumption: As the wireless radio communication consume is big and the actual battery capacity (considering an adequate size similar to the motes one) is reduced, the global consumption has to be accurately reduced in order to provide the motes a lifetime long enough. This is the target of different research works about different energy battery systems and Energy Harvesting systems, as it will be specified later in Chapter 3.

- Mobility of nodes: Taking advantage of the ability of the WSANs to provide dynamic connections it is feasible to provide the ability of mobility to the elements conforming the network in exchange of some more elaborate algorithms to control the variation of the set of elements conforming the different clusters with time. This can be specially applied to *actors* and mobile sinks to improve the network system by reducing latency and consume (by shortening the mean distance for communications).

- Data routing: The motes are designed to be able to discern how to send their information to the sink, but also to send the information from farther motes to the sink when, because of distance, a multi-hop communication is required to reach the final destination. The multi-hop protocols have

to be well designed to improve not only the distance, and thus the consume, but also to control the average throughput in the network to avoid bottle-necks and other typical communications issues.

The characteristics just defined are the ones which defines properly a WSAN. However, are others the parameters we need to improve by optimizing the network:

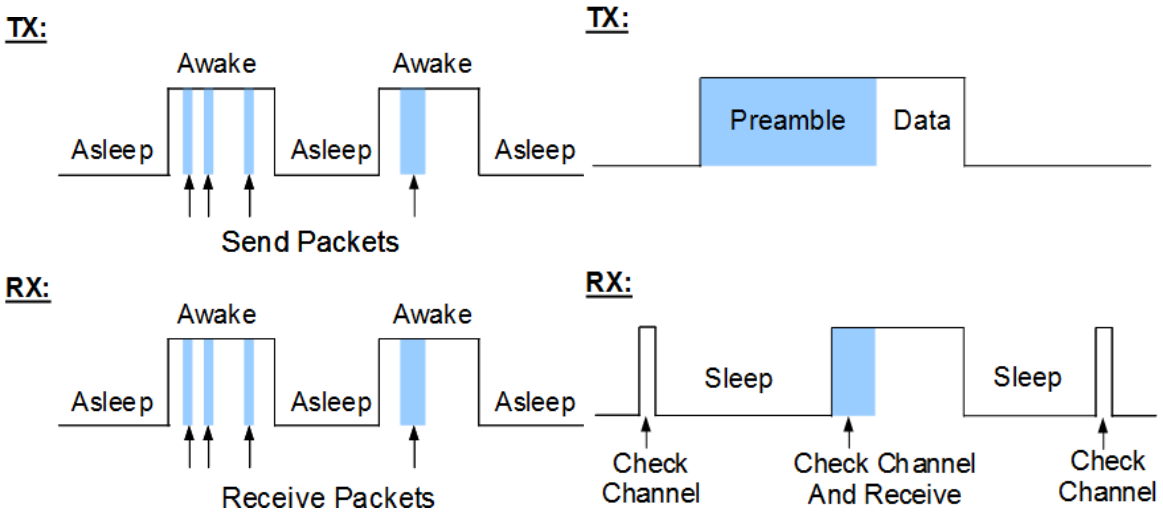
- Lifetime: Represents the time, from set up to the general malfunction of the whole network, do to a global discharge of the batteries or some elements stopping to work because of other reasons. The boundary between a simple failure and the end of the network lifetime can be defined as a percentage of errors during a certain interval of time or a specific grade of violation of the QoS.

- Duty cycle: Indicates the ratio among the time in which one sensor is on (sensing, listening the radio or transmitting) and the time it is set to sleep mode to safe as energy as possible. Different sleep modes can be set from the one just setting down the radio while still sensing to others where just the clock is still working. The increment of the sleep mode and thus the reduction of the duty cycle provides a longer lifetime to the network while compromising the freshness of the data provided to the data sinks. Also the communications can be synchronous (which will need a certain clock control to keep the timing) or asynchronous (no need of a special clock always on but larger preamble packets to set communication), and their chronographs appear in figures 2.1a and 2.1a respectively and imposing different communication protocols.

- Quality Of Service (QoS): Is the ability to provide variable priority to different nodes, or to guarantee a certain level of performance to a data flow. For example, a required bit rate, delay, jitter, packet dropping probability and/or bit error rate may be guaranteed. Not being able to guarantee a certain QoS will compromise the communications and, hence, the global efficiency of the network, even arriving to consider its death. Many are those problems risking a certain QoS:

  [Low throughput]: Depending on other users load variation, the bit rate (the maximum throughput) that can be provided to a certain user stream might be too low in order to maintain life-time or high-speed communications.

  [Dropped packets]: The information sent can be compromised because of packet crashing or if the receivers buffer is full, reclaiming for a re-transmission of the packet and altering the communication. It can provoke delays, data loses and order alteration of the packets.




(a) Synchronous mode

(b) Asynchronous mode

Figure 2.1: Duty cycles chronographs for WSAN

[Errors]: As the media where the packets are sent is compromised by both interference from other users and noise, sometimes the lecture of the data done by the receiver can be erroneous inducing to package errors. If those can be detected the packet will be dropped and a re-transmission will be asked if possible.

[Latency]: Due to the multi-hop communication, possible packet drops and retransmissions, bottlenecks and other issues, the time comprehending from the initial transmission to the final reception, which we know as latency, might compromise some communications such as VoIP or online gaming where the throughput can be reduced but the time delivery is highly important.

[Jitter]: Packets from the source reaches destination with different delays, depending on its position in the queues of the routers. This unpredictable variation in delay is known as jitter and can seriously affect the quality of streaming audio and/or video.

[Out-of-order delivery]: When some information is divided in different packets to be sent through the network, those can take different times and paths to arrive to their destination. Then, a special control over the order of those packets must be done to reproduce properly the information received. This shouldn't be a problem for regular data but in applications where the time is important it has to be done in a time efficient way, in applications such as video and VoIP streams where quality is dramatically affected by both latency and lack of sequence.

## 2.2 WSAN Architecture

The WSAN, due to its wireless communication system provides a perfect infrastructure foundation to generate any kind of possible interconnection network. Releasing the network from the physical media imposed by the previously used cabling to interconnect them, provides a new full liberty interconnection design which can be reached at a theoretical zero cost compared to a less global connections network.

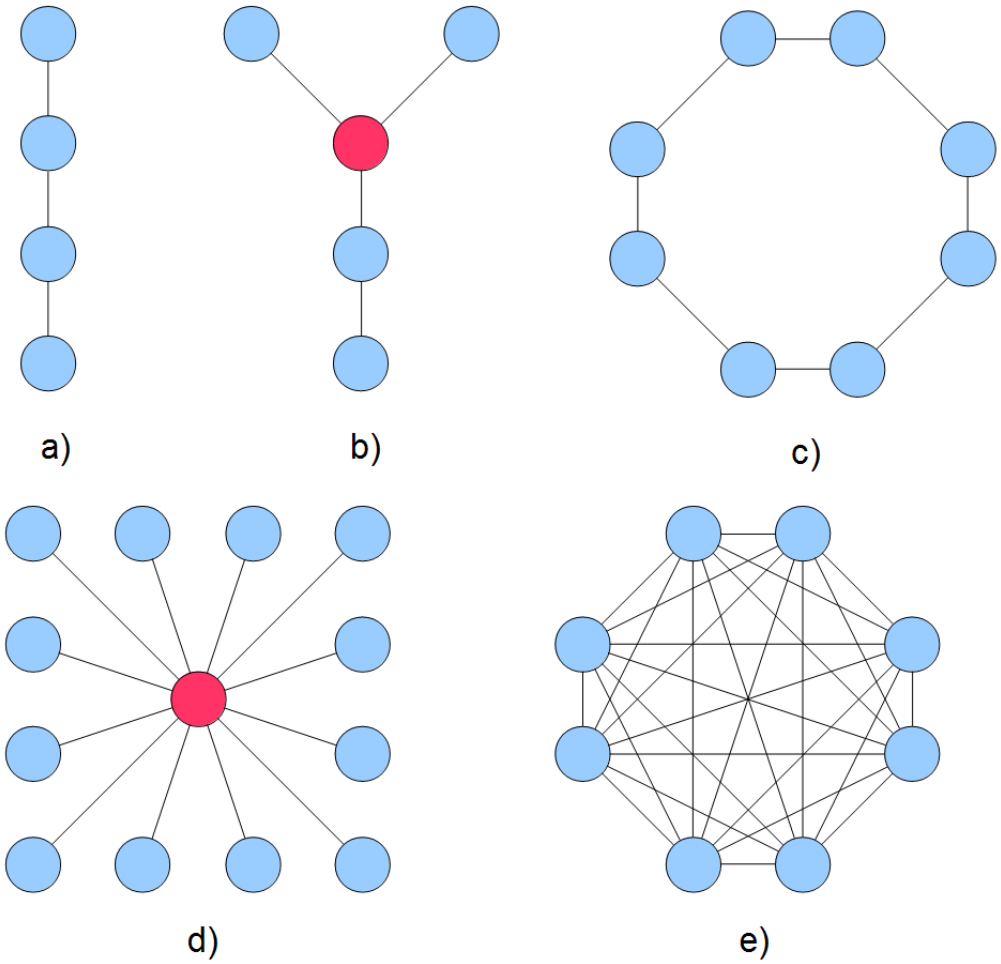



Figure 2.2: Network architectures: a) chain, b) tree, c) token ring, d) star, e) mesh

Then any kind of the typically used networks for communications (as seen in Figure 2.2) can be built.

From all the cases we can observe in Figure 2.2, a star structure (Figure 2.2.d) with the data sink as the central node might be the fastest one for the transmissions, reducing the average latency, but distance might be an inconvenient in large scenarios. Furthermore, as the communication media is shared, there would exist a large amount of packet crashes, deteriorating the communications due to the space shared

and the bottleneck behavior of the sink.

The opposite scenario is represented by an mesh structure (Figure 2.2.e) where all the elements are interconnected to the rest. Although it is totally feasible, sometimes is better to restrict the connections in order to avoid bottle-necking (a node trying to receive information from a large amount of transceivers might not be fast enough to process all the data).

Then, considering the two previous cases and merging them the best solution arises from those schemes. Considering the problems of packet interference and crashing and also the attenuation, it's trivial to comprehend that in small regions a direct connection with a token ring (2.2.c) or Y-pattern (2.2.b) can be used because of the small amount of elements (and thus a reduced probability of packet interference). On the other hand, for large amount of distance and elements a multi-path and multi-node network, similar to the star (2.2.d) one must be used. Then, clustering our network in different sub-networks we can design each of them as a wheel system and then use the sub-network heads to create a whole scenario star network.

However, as those networks are fully dynamic it is possible to have variable sub-network heads in different time instants depending on the load of data each point has to process in order to improve the QoS, the latency, the lifetime (by reducing the amount of work for low battery nodes) and others.

Observe that in Figure 2.2 the red circles denote for 2.2.b and 2.2.d the cluster heads while in the other cases each of them works at the same level.

Once considered the general inter-communication infrastructure of the Wireless network, we have to distinguish the different elements (as seen in Figure 2.3) forming it:

- Sensing motes: conforms the base of any sensing network, deployed to sense and monitor events occurring in the scenario and obtaining information to provide to the databases. Are formed basically by a sensor, or a board with different sensors, a radio interface to communicate through radio frequency and a low-power microprocessor to process the lectures from the sensors and create the packages to be sent by the radio interface

- Data routing motes: motes, which can be simultaneously sensing, destined to forward the information from other sensor motes to the final destinations facilitating the wireless communications. It can merge different packets in a single one to save some energy in transmission in expense of more processing in the mote or just forwarding the information as it has been received.

- Special motes: some motes, apart from the previous ones, can be set to control the different clus-

ters, monitor the network and make decisions upon the evaluations done. Due to the higher amount of processing power required they have to be accurately designed and used to provide a real improvement to the network. Here is where the *actors* might be included as they provide other functions to the network apart of the sensing and raw data transmission.

- Databases and processors: Are the final receivers of the data generated by the sensor motes, can be only one or more depending on the design of the net and will process the data to finally deliver the user the desired information.

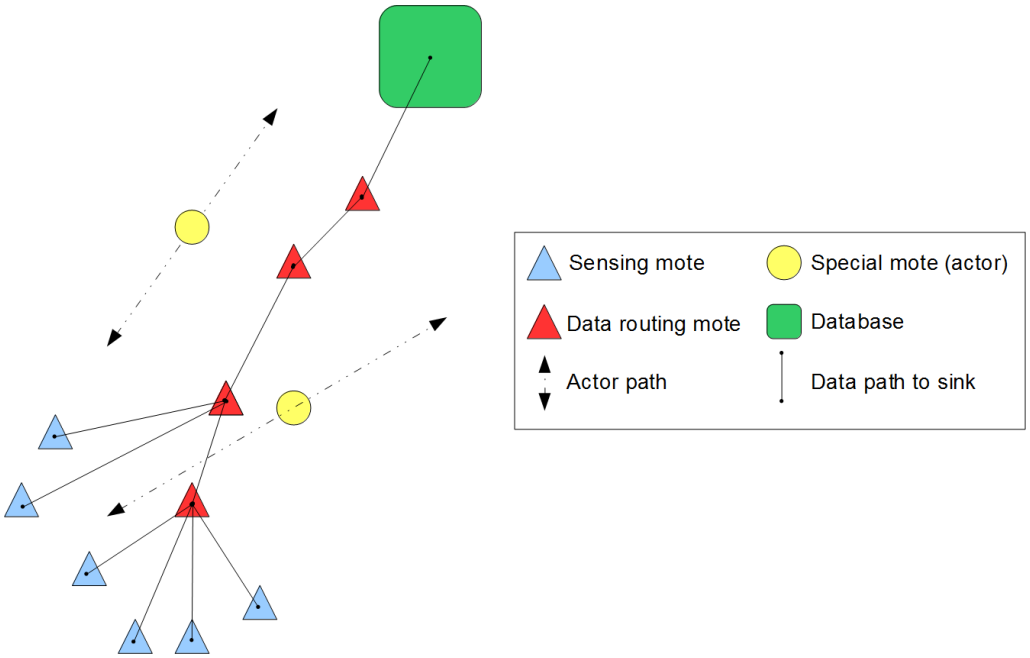
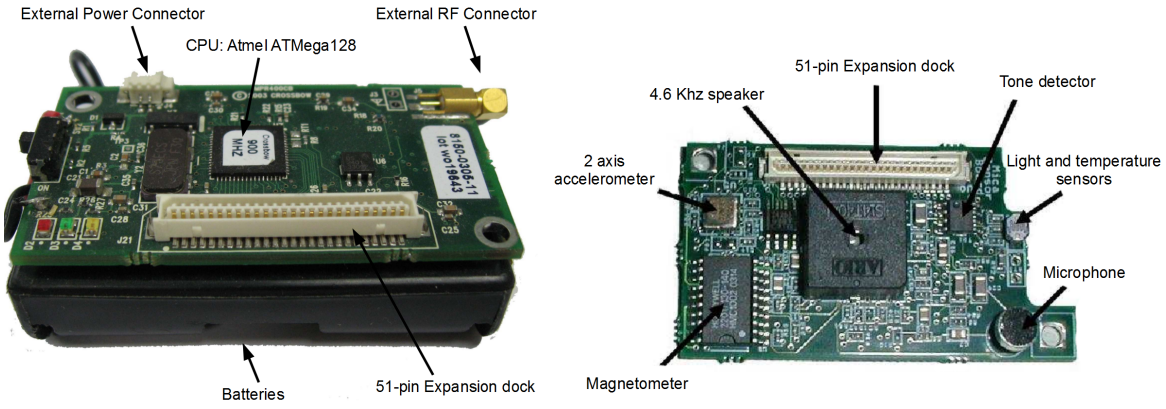



Figure 2.3: Network components

### 2.2.1 MOTE components

The motes are the only elements in a WSAN which generate data and transmit it to the databases. Different families have been already broadly studied (MICAz, MICA2, TELOS, ...) but another are being designed with lower power requirements and more efficiency.

Even though, all the different families consist in similar designs. Usually are programmed with the similar developing languages, being TinyOS the actual leader to program their microprocessors.




(a) Mica2 mote

(b) MTS310 Sensor board

Figure 2.4: Mica2 and MTS310 sensor board elements

Having MICA2 mote as a reference (as it is the one used for this project and we can see it in Figure 2.4a) we can differentiate these parts:

- Processor: It contains a processor (Atmel ATMega 128 in this case) which is capable of low-requirement processing executions enough to prepare the packets to be sent.
- Power source: Can work with batteries implemented on the own mote or with external sources, providing a way to work with Energy Harvesting circuits.
- Radio system: Contains the radio system and antenna capable of communicating between different motes.
- Sensor board: With a 51 pins Hirose connection, a external sensor board can be attached to provide more information.

  [Sensors]: Depending on the board used different data can be sensed. With MTS310 board (see Figure 2.4b) 2 axis accelerometer, magnetometer, microphone, light sensor, temperature sensor, tone detector and a speaker are included.

  [Converters and calibrators]: As the sensors included in the board are analogical, analogical to digital converters (ADC) are required. Also calibration systems for the different sensors might be necessary.

- Other elements: Not mandatory elements as GPS can be useful in some networks to provide more information or accuracy.

## 2.3 WSAN Applications

In the last years, due to the frenetic evolution of the Wireless Sensors and *Actors* Networks caused by their high level of application feasibility in complicated, high variance, and different scenarios, the list of applications where WSAN are being used have grown up very fast.

Due to their low processing capabilities they are not still being normally used for entertainment information sharing or similar but to support different kind of scenarios where the intention is to monitor or to track events and elements in the surroundings.

As we can observe in Figure 2.5 two categories can be easily found to split and categorize properly the WSAN applications, which are:

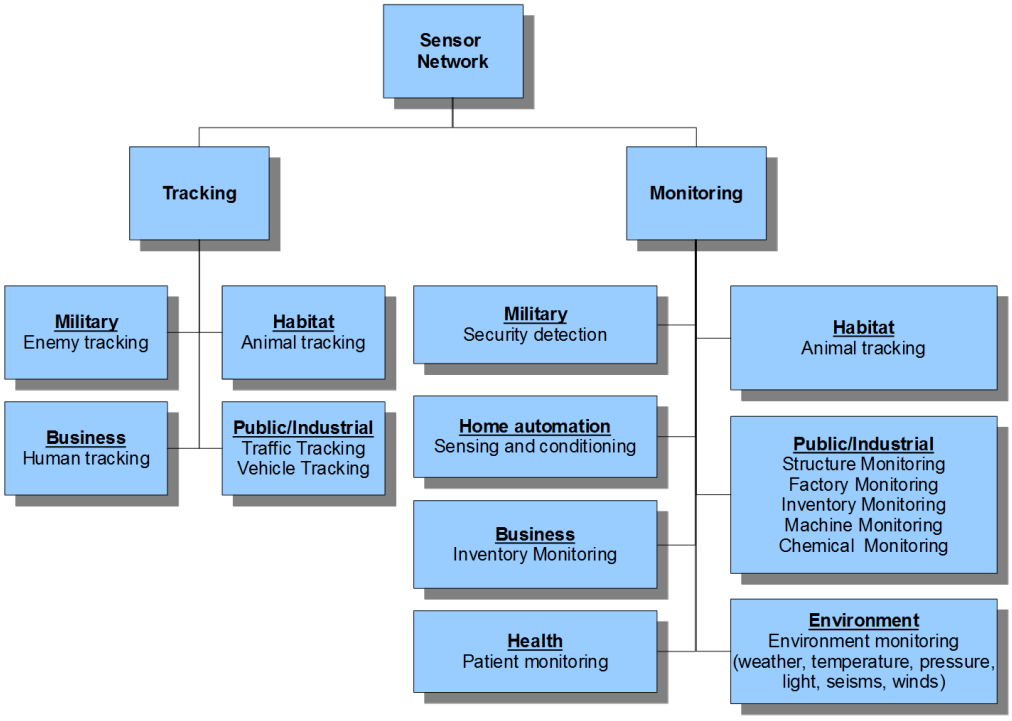



Figure 2.5: Application categories of WSAN

- Militar: Used to control the different changes that can happen in a region, specially for security

protection (over unknown territories in attack operations) but also used to track movements and intrusion detection (over known scenarios when defending).

- Animal care (habitat): Provides the possibility of control species in large habitats like forests or other natural places without a big infrastructure.
- Home automation: Using the large amount of possible sensors and the possibility of monitor the data obtain considering the emplacement of each lecture it's easy to control ambient in temperature, light, humidity, and other comfort being a good resource for home automation, specially for models applied after the house construction where a wired model would imply a big reform of the entire house through floors and walls. Also the human tracking can be applied to be modifying some parameters in the house depending on the presence or absence of people in the rooms, and when absence is ensured it can be also used to detect intrusions.
- Business: Here the application is similar to the home automation but applied to business, enlarging the traceable elements from human to also objects being able to control stock.
- Industrial: Used in factories to control if any chemical of physical hazard is happening, any kind of alarms, the actual state of the machines, inventory, the structures, security...
- Health: The small size the motes can reach facilitates the possibility of controlling the patient biorhythms and constants. Also it is even possible to use subcutaneous sensors thanks to its wireless conditions.
- Environment: Is highly used to control big extensions of territory in order to control migrations, different hazards as floods, seismic activities, fires, tornadoes and similar through the different sensors.

## 2.4 Issues of battery powering in WSAN

Since all the elements conforming a WSAN are mobile, it is unfeasible to provide them energy from high-power sources through wired connections. Instead, we must provide them batteries or other systems which can provide a certain level of autonomy.

While it could seem correct to recur to the utilization of battery sources as we already do in a lot of cases surrounding us, from small electronics to vehicle batteries, the use of batteries for WSAN implies

a bunch of issues which forces the designers to find other solutions. Some of this problems concerning the use of batteries are the next ones:

- Nodes dispersion: Since the WSAN scenarios can be really large both in elements and extension (up to hundreds or even thousands of meters) the process of replacement of batteries in the network could be too long, even comparable to the battery life itself. It signifies a high cost maintenance, both in time and money, not affordable in most of the situations.

- Variable consume ratio: As all the nodes will have a different consume pattern (some nodes being the root for different communications trees will consume more because of the requirement of processing all the data received from their branches and send it towards the sink, different power levels depending on distance, among other issues) not all the batteries will need a replacement at a same time, which would imply a strict constant control of the battery levels and a high coordination to replace only the batteries which really need to be replaced (to have a efficient use of each battery) and at a certain moment to reduce the time that node is down.

- Accessibility: While some networks' nodes are easily reachable, in general WSAN are set up to control scenarios where wired sensors cannot be set. Consequently, the access to the nodes may be a handicap, because of different reasons: it can be out of human range, it can be inbuilt in different materials or inserted under skin in humans and animals. It means a big trouble to its access and hence the number of times it has to be reached and manipulated has to be reduced.

- Battery wearing: Batteries, which are formed by different chemical products, suffer a important wearing with time which involve a mandatory replacement of batteries instead of a simple recharge and thus a increment of cost per node with time.

- Batteries hazard for environment: Also because of the chemical products required to create a battery, there exists some environmental hazards. While the batteries are designed to suffer no leakage, the different weather hazards suffered will wear and tear out the insulating materials of the battery provoking with time an inevitable pouring of contaminating products to the environment where the nodes are set. It can be importantly dangerous when considering under skin implementations or others in nature like forest or aquatic scenarios.

All this problems the WSN suffer with batteries have forced to evaluate different possible alternatives to provide the required energy to the remote elements.

Once eliminated the possibility of batteries or wired connections all the cases where the energy source is auto-containing the energy released to the circuit are obsoleted. Then, only one solution can be possible: find systems capable of energy harvesting or gathering and offer this converted energy to the circuit. Those are the circuits known as Energy Harvesting circuits which we will discuss in detail in Chapter 3.

Basically those circuits will get the energy from different sources as it is explained in Section 3.2 and convert it with the elements explained in Section 3.1 to electric energy which will feed our circuit.

# Chapter 3

# Energy Harvesting

Due to the last years advances in technologies and the concept developed by Albert Einstein which claims the duality of energy and mass, where each object or wave implies an energy existence, a group of researches have lead to some systems which gather and transduce their energy into electric energy profitable for different circuits.

Energy Harvesting encompasses all the different technologies which, through different architectures (explained in Section 3.1) transduce the energy existing in different sources (see Section 3.2) into electricity and providing new systems capable of being long-lasting energy sources to electronic gadgets and even replacing batteries, which have become one of the most constraining issues in the last year devices design.

Finally in this Chapter is also introduced which are the implications of Energy Harvesting system introduction in the WSAN systems.

## 3.1 Energy Harvesting architecture

In general the energy harvested from any source goes up to microWatts or even miliWatts and thus is not sufficient to be used directly. Then the concept is to gather enough energy before using it, storage it and then consume it. With this system, we can divide any Energy Harvesting system in three parts:

- Energy transducers: As specified before different elements can be used depending on the initial energy source, always with the finality of obtaining electricity. Here the level in Watts or Volts won't be usually enough for the system so a voltage multiplier or some power booster circuit will be required. Those are some of the most usual energy transducing systems:

[Turbine]: Formed by a group of blades which rotates pushed by an applied force (wind, water or steam streams among other possible sources) provokes the rotation of a magnet, creating a variation on the magnetic field and thus inducing a current over a static wire set up inside the variable magnetic field, creating electricity (it is also possible the symmetric case with a moving cable and static magnet).

[Vibrating spring]: Formed by a magnet attached to a spring and a static wire, uses the same principle explained for the turbine, the vibrations applied to all the system implies a vibration in the spring, which will move the magnet and induce a current in the wire. As any vibrating system it is important that the oscillations work near to the resonance frequency to obtain a sufficient percentage of energy.

[Piezoelectrics]: Are materials capable of producing energy when under pressure or to change their shape when electricity is applied. Are very useful to gather energy from elements under pressure as it can be footfalls, variation pressure in vehicles, buildings and others.

[Pyroelectrics]: Taking advantage of the ferroelectric behavior variation with thermal changes, pyroelectrics transduce thermal variations into voltage or current which can be stored for later use.

[Thermoelectrics]: It was discovered that a thermal gradient formed between two dissimilar conductors produces a voltage because of a diffusion of charge carriers. The flow between the different thermal pieces creates the desired voltage difference.

[Photoelectrics]: Consisting on the variation of the charge carriers inside a dielectric when a light is applied, due to the excitement of the photons induced, currents are generated, one to balance the variations, the other because of the electrons excitement by the photons energy.

[Antenna]: Is an element which, due to the electromagnetic waves received, a current is induced in its interior. It is also sustained to electromagnetic field formulae as the system used in the turbine and the spring vibrations but requires a special tune in length to work properly at a certain frequency, being very selective.

- Voltage Multiplier: Often the energy gathered is too reduced to be directly used or stored and a special stage, boosting the voltage, current or power is needed. Specially for the radio frequency systems where antennas are used there exist some Voltage multiplier circuits to do this work (see Figure 3.1) which provides a higher voltage level and, if well designed can power up from miliVolts

to 2-3Volts which are the typical values required for the elements in a network (depending on the Vdd levels for the electronics family used going from 5 downto 1Volt).

- Storage: Sometimes the energy is not required at the same moment it's gathered because the device is in sleep mode or doesn't require the harvested energy. Then this energy has to be stored in batteries or super-capacitors to be used later or it would be wasted.

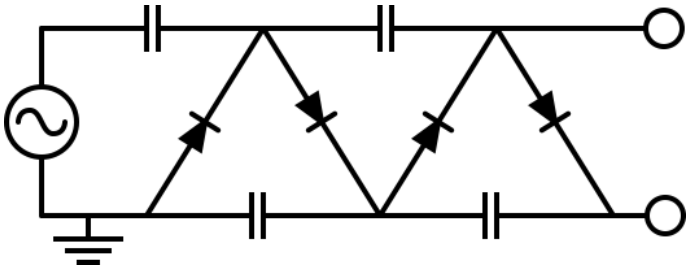


Figure 3.1: Voltage multiplier circuit schematic

## 3.2 Energy Harvesting sources

Starting from the Einstein equation demonstrating that everything contains energy, it's easy to imagine how, if we develop the adequate tools, we can gather energy from very diverse sources.

While some have been already exploited for a long period due to the facility to use them, others have been only studied in the last years due to the high complexity of the equipment required to gather energy from them. In Figure 3.2 we can find different possibilities, all of them explained here:

- Heat: Specially extracted from fire flames since the prehistoric age but also from other hot materials, this resource of energy becomes one of the more basic ones if used directly, but with some transducers it is possible to storage it like pyroelectrics and thermoelectrics. On the last years, subcutaneous implants of WSAN have started to use body heat as a energy source.

- Kinetic energy: Considering the energy which implies movement, it is possible to transduce it to electric energy. Different are the sources used to transmute the energy (water streams, water steam, wind) and using a turbine system to transduce the energy, or an anemometer.

- Mechanical: A long list of sources can be harvested by their vibration, mechanical stress and mechanical strain. Those sources includes the human movement, wind forces, other mass forces on

Figure 3.2: Energy Harvesting sources [7]

movement, seismic movements, internal body vibrations as heart beats through the veins, breathing, ...

[Vibrations] The vibrations induced to the converter are transduced to electric energy through the vibrating spring system. Profitable only for rhythmic oscillations to avoid destructive vibrations which will attenuate the spring vibration reducing the efficiency.

[Stress forces] Applies gauges which generate energy when its geometrical conditions vary under a stress applied. Again on of the most common is to apply some magnetic field generators (magnets) and produce induction currents but other elements which produces energy under stress can be used as well, like piezoelectrics.

- Light: Light produces two ways to gather energy, the first one, really ancient, uses the heat from sun light to heat water and then work as explained in the heat point. The other, also well known is the photoelectric effect and is the one used in the solar panels.

- Electromagnetic: Due to the big evolution in the telecommunications our society is suffering, a important increment in the electromagnetic spectrum density surrounding us (specially in large populated areas) such as broadcast radio and television signals, mobile telephony or wireless net-

works. With specially designed circuits, much more complicated than other elements explained before, we can gather part of the free energy in wave form surrounding us and use it in our own profit. To do this a special element, an antenna is required. The big limitation comes up with distance as those signals suffer a big attenuation and the circuits to gather the energy are not very efficient, that's why those systems can only be used in close areas to big populated regions where the communications signal density is higher. The other option, which is the main topic of this research, is to use actors designed specifically to transmit the required radio frequency signals.

It is also important to consider the nature of each harvestable source we can find. There are two important characteristics to consider:

- Prediction Determines the capacity to anticipate which will be the source pattern of harvestable energy before it happens. Some are totally unpredictable like vibrations while others have a repetitive pattern like sunlight.
- Control Evaluates the ability of the user to govern the source emission or its reception. Also here we can found sources totally uncontrollable as seismic vibrations, partially controllable like sunlight through lens or wind through tunnels of fully controllable as the RF emissions.

Note how the different energy sources from human body have different behaviors depending on their condition:

- Active: Involve all the possible actions a human can govern and decide when or how to do them. Pressing a button, footfalls or joints movement are some examples.
- Passive: Groups all the sources a human cannot control, from heart beats, to veins dilatation and lungs and chest vibrations with breathing.

### 3.2.1 Motivation to use Radio Frequency Energy Harvesting

From all the Energy Harvesting sources available with the actual technologies explained in Section 3.2 only some of them are fully controllable and thus reliable as a long term primary energy source for our systems.

Checking Table 3.1 we find different options to achieve both a good level of prediction and control of the Energy Harvesting. The most important ones are the human motion through stress forces, the

| Source | Prediction | Control |
|---|---|---|
| Heat | On living beings high prediction | No control |
| | Variable upon source | High control |
| Kinetic energy | Low predictability in nature sources | Low control, redirection of spades to maximize incidence |
| Vibrations | No prediction for nature sources | No control |
| | Low prediction of machine vibrations | High control |
| Stress forces | No prediction for nature sources | No control |
| | On demand for body motion, footfalls | Full control |
| | Periodic for heart beats, blood pressure | No control |
| Light | Cyclic every 24 h for sunlight | Partial control, using lens and mirrors for rays concentration |
| | On demand | Full control with artificial light |
| Electromagnetic | On demand | Full control of emissions |

Table 3.1: Prediction and Control of Energy Harvesting Sources

light from artificial sources and the electromagnetic fields. Also wind, although unpredictable in specific moments, have some trends in places of the world in specific seasons so it has to be considered too.

While all the possible energy harvesting produced by human bodies (both passive and active sources) provide a good energy source for wearable or subcutaneous WSAN, usually networks are disposed in large territories and the human sources cannot be considered at all.

Finally from the three big energy sources, which are Sun light (or artificial light), Wind and Electromagnetic fields (through Radio Frequency Energy Harvesters), different conditions have to be considered:

- Light: Internal housing case can be considered but it depends on a artificial light source which implies a higher consume than just plugging the sensors to the energy lines. For the solar case latitude and the average weather of the scenario have a high importance in the final decision (check Table 3.2) to improve the harvested energy. Also the high production cost of a solar cell (the process in a Clean Room is really high cost) forces to find other alternatives when possible.

- Wind: Again like in solar light situation, the position in the earth have a remarkable importance.

When in sea or high lands a good power level can be achieved while in regular scenarios, with obstacles for the wind, efficiency will decrease importantly. Apart all the wind turbines designed to this time requires a high level maintenance cost.

- Radio frequency: Is important to consider the distance here as the energy we can gather from Radio Frequency electromagnetic waves decreases in a quadratic way with distance. Also the different combination of sources is not always constructive but sometimes destructive depending on the phase of all the components. This conditions may seem to indicate Radio Frequency Energy Harvesting to be a wrong candidate due to the need of a high dependence with distance to Radio Frequency towers or the cost of construction of own towers for our system. Nevertheless the cheap cost of Radio Frequency Energy Harvesting circuits is a important indicator of all the opportunities this system can provide to gather energy. Furthermore, in the last years the investigations are also oriented to expand the bandwidth where this circuits work, from radio bands to other frequencies.

## 3.3 Energy Harvesting in WSAN

As it has been already introduced, the WSAN suffers of a high limitation in terms of energy due to the actual capacities of batteries which are applicable to the motes considering the size and the hazard ambient conditions they can suffer when deployed in the scenario. Furthermore, batteries tends to wear out with time implying a high-cost maintenance to replace batteries, which in some cases is even harder due to the difficult access to motes (large scenarios, subcutaneous implants, inbuilt motes, ...) forcing to recur to other energy sources.

Due to the inadmissibility of wire connections to high-energy sources due to the mandatory wireless conditions, the main issue with WSAN energy is to provide a system, full autonomous, capable of provide energy in a regular basis and for a longer term than a regular battery, keeping the volume inside some terms acceptable for the motes mobility and prepared for the different ambient hazards it can suffer.

During the first years of the WSAN the first evaluated option was to study different energy-aware protocols (recurring to low power components, adequate duty cycle and radio power selection, ...) in order to maximize the amount of energy inside the batteries.

After some research it was obvious that the improvements in energy-aware, while really profitable and interesting, weren't enough to provide the WSAN the awaited self-control and autonomy for the

| Energy source | Power level |
|---|---|
| Solar cells (sunny day) | $15\,mW/cm^2$ |
| Solar cells (cloudy) | $0.15\,mW/cm^2$ |
| Solar cells (indoors) | $0.006\,mW/cm^2$ |
| Solar cells (desk lamp $<$ 60 W) | $0.57\,mW/cm^2$ |
| Footfalls | $330\,\mu W/cm^2$ |
| Vibration (microwave oven) | $0,01-0,001\,mW/cm^2$ |
| Thermoelectric $(-10\circ C)$ | $15\,\mu W/cm^2$ |
| Acoustic noise$-$100 dB | $9,6-4\,mW/cm^2$ |
| Wind | $0.8\,mW$ |
| Finger motion | $2.1\,mW$ |
| Vibrations in indoor | $0.2\,mW/cm^2$ |
| Exhalation | $0.4\,mW$ |
| Breathing | $0.42\,mW$ |
| Blood Pressure | $0.37\,mW$ |
| Radio frequency (@ $20\,dBm$) | $75\,mW$ |
| Radio frequency (@ $0\,dBm$) | $0.5\,mW$ |

Table 3.2: Different power outputs for Energy Harvesting systems [19, 20]

motes. Here is were, through the different Energy Harvesting systems (called EH in this thesis) and an efficient control over the scavenged energy, the system could get a theoretical infinite lifetime.

### Design considerations

When designing a WSAN Energy Harvesting infrastructure it is mainly important to consider which are the requirements in order of Voltage, time and stability and consequently choose the most adapted system.

As a WSAN must be totally autonomous, there are some aspects which have to be designed accurately to avoid a malfunction of the network when it is possible to be avoided. From the different parameters related to a WSAN two are directly responsible of the design conditions applied to Energy Harvesting:

- Voltage: The digital circuits, because of the duality model used to work in binary require to different robust levels of voltage to avoid problems with slow charges, oscillations and noise. This causes the requirement of a certain voltage to be provided to the electronics to work properly. This voltage, which years ago started working at 5Volts has gone down to 2Volts as the one used in the electronic family in this thesis or even $<$ 1Volt for the most advanced technologies. This voltage level has a direct influence in the processing power consume as it has a quadratic dependence with the voltage. Depending on the Harvesting system and the voltage requirements two different Harvesting models can be used:

  [Direct use]: On some systems where the amount of energy harvested is enough to reach the voltage levels most part of the time it is possible to use the output of the energy harvester directly to feed the circuits. If some problem with energy happens the circuit will go to sleep mode disrupting its function.

  [Storage and use]: If the energy is really small compared to the need one the best solution is to wait a sufficient amount of energy to be gathered and stored until it reaches the minimum level required by the circuit, use it and go to sleep again. It will imply a working model based on long sleep times and short bursts of awake time.

- Consume: The final goal is always to increase the lifetime by reducing the consume, trying to reach the crossover point among the consume and the harvested energy. This can be reached with different arrangements, some of them are:

  [Duty cycle]: By reducing the time the sensor is awake against the time it is sleeping during a full cycle it is possible to reduce it's consume. However, there is a counterpoint compromising the data freshness as the average time between data sensing and transmission will get increased and then the data processed will diverge more from real-time even obviating some punctual short term events.

  [Transmission]: While reducing the frequency of reading and transmission helps, another parameter, the transmission power, has a great importance in the consume, a way to reduce it can be using more nodes in the middle to reach finally the sink. This alone wouldn't reduce substantially the consume but applying diverse packet merging protocols, where some tree nodes groups the received packages to send them to the next destination can reduce both the consume in the warming up of the radio system and all the energy spent to transmit the different packet headers

as it will be reduced just to one by the cost of a slight increment of the packet headers.

Then these conditions will imply some consequences compared to the old network design.

The harvestable energy distribution in the different regions of the scenario acquires a high importance as it will modify the topology of the network. While, before harvesting, the networks usually required of overpopulated regions around the events and different data paths to compensate the mote deaths due to the batteries wearing totally out, now the network will have to be constraint to the energy level map around the scenario in order to increase the Energy Harvesting efficiency.

This not only influences the development but also the criteria for packet routing around the network. Instead of considering the motes residual energy level by itself, a ratio among the residual energy level and the rate of Energy Harvesting has to be used to consider in each moment which might be the best candidate to create the packet route. This way the different data aggregation trees conforming our subnets to deliver the packets to the sink will suffer a fast and constant dynamism and hence the clusters will evolve with time as well.

# Chapter 4

# Simulation Setup

This chapter orientates the reader through all the different concepts dealt with during the evolution of this research project. The set up of the scenario is explained from its foundations, explaining the deployment of the sensors and the generation of the Event points (Section 4.1) which have to be monitored and defines the different sub-networks, how is developed the creation of the sub-networks (Section 4.2) using the Voronoi tessellation algorithm to provide a lower-cost and energy-efficient scenario analysis, how the different moving models work (Section 4.3) and the process of *actors*' deployment for each moving model defined (Section 4.4) and finally the formulae required during the simulation to process both the moving consumption and the energy waves attenuation which affects the obtained power by the energy harvesting circuits (Section 4.5). At the end, in Section 4.6 the algorithms used to obtain and process the data from the MATLAB simulations and create the different figures displayed during this document are also explained.

## 4.1 Sensors and events generation

The most important elements of a WSAN, as specified in Section 2, are the sensors (also called motes) which compose the network nodes and sense and send the information to the databases to be processed. However, different configurations can be set to work in different modes, like having more motes near to the monitored areas were the Event occurs (Event points) to have more information about the events, or having the motes spread disposed to facilitate the data-hopping through the motes to the data sinks.

As all the possible configuration sets are geometrically really different, the final option to emulate the sensors network has been the deployment of them randomly following a uniform distribution inside

the scenario. This way the network can be working both sensing and providing data-hop paths to save the information obtained.

For the set of Event points, which apart of being the points where events occur are also the reference points used to create the moving models, are also set following a uniform random distribution inside the scenario, providing this way a more relaxed and general set of evaluated scenarios.

Once the Event points are set it is time to start the design of our moving models by dividing the scenario in sub-scenarios through the method exposed in the next Section.

## 4.2 Voronoi Tessellation

Since WSAN size can achieve great bounds because of their number of both sensors and *actors*, sometimes is computationally unfeasible to deal with the process of whole network at once. From all the possible ways to split the scenario in different sub-scenarios and treat them independently, one considering the distance as the classifying criteria to choose the best group affiliation has been chosen, having an easy adaptation to all the possible scenario configurations.

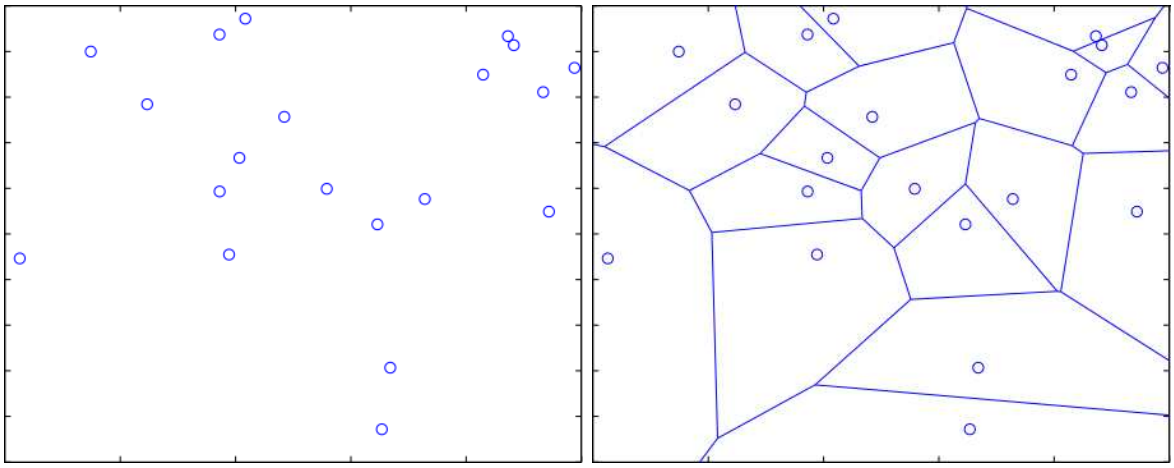
As the network highly depends on the different events happening through the regions, because of sensors purpose is to sense those events and send the information obtained to a high-computational level sink to be processed, we have decided to create the fragmentation using the Event points as the center of each sub-scenario.

This way, using the Voronoi algorithm we can ensure that being $S = \{p_1, p_2, ..., p_i, ..., p_n\}$ the set of points representing the Cartesian coordinates of all the Event points, the set of all sensors closer to the Event point $p_i$, noted as $V(p_i)$ will be closer to that Event point than any other belonging to $S$ [5].

$$V(p_i) = \{x : |p_i - x| < |p_j - x|, \forall j \neq i\} \tag{4.1}$$

Obtaining the set of sensors ($V(p_i)$) represented by their closest EP (as seen in figure 4.1a) we provide a good way to refer each set of sensors during the simulation. So, instead of using each one of the coordinates of the sensors, just the ones of the set $S$ representing that sub-scenario are needed to process all the calculations relative to the power management required by the *actors* to provide an appropriate level of energy so the EH circuits can achieve their goal of gathering a certain amount of power and become a long-lasting even infinite energy source to the sensors conforming the network.

The set of sub-scenarios set by the Voronoi algorithm are displayed in figure 4.1b using the EP



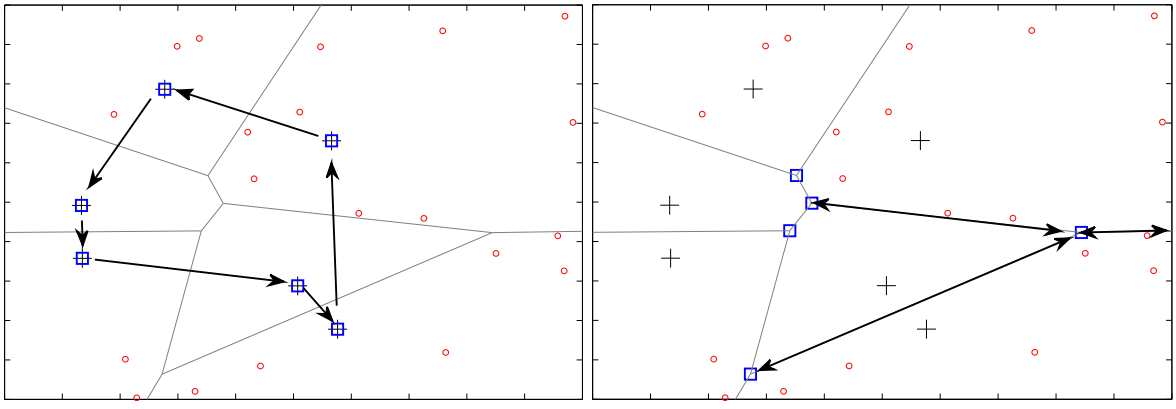
(a) Event points

(b) Voronoi cells with EP as centers

Figure 4.1: Voronoi tessellation

coordinates displayed as circles in figure 4.1a.

## 4.3 Moving models



(a) CM moving model

(b) EM moving model

Figure 4.2: Moving models schemes. *Actors* (squares), Event points (+), Sensors (o) and boundaries of the Voronoi cells (grey lines)

Once the scenario has been evaluated and divided in the different sub-regions, the next part of this project consists in decide how to move the set of *actors* around the scenario in order to improve the signal received by the sensors.

Considering the distribution seen in figure 4.1b is easy to observe how two different data sets can be used. On of them is directly the set of Event points while the second one uses the set of the Voronoi cell edges to have a reference to move through.

### 4.3.1 Center to center moving model (CM)

Considering this first moving model, from now on called as *center-to-center moving model* (CM), the set of *actors* will move along straight paths formed by each couple of EP forming a path based on a traveling salesman problem algorithm (TSP) [6] which iteratively process which could be the lowest cost closed path traveling from one to another EP visiting all of them only once before closing the path (see Figure 4.2a).

With this algorithm and considering as cost the distance among each couple of EP, the final result provides us the shortest path around all the EP and thus the best moving path around all the EP when trying to minimize the time and maximize the coverage over the sensors.

The main reason to try to travel form each EP to the other ones is that those sensors which are placed close by the EP might need a longer EH power level as they are supposed to be a higher power consumer. This higher consume ratio is caused by the larger amount of data sensed they have to process and send through the radio channel while other sensors which are deployed in farther areas to the EP should only have to work on the data forwarding from the EP sensing motes to the final data sinks.

### 4.3.2 Around edges moving model (EM)

In the second moving model, called as *around edges moving model* (EM), the *actors* move along the edges of the Voronoi cells.

This alternative moving model is created to deal with a big problem observed with the first moving model. As the model focuses on the EP and surroundings to create the moving path, all the sensors which are not close to an EP or near the path described before using the TSP will suffer a energy deprivation due to the large attenuation all the energy sent suffer before reaching them.

Those sensors, while not really determinant at the function of sampling the events because of their larger distance to the Event points can be really useful in terms of data-aggregation [2] and data-forwarding or data-hopping [4, 13] as without them the sensors could never reach the data sinks because of radio transmitting power limitations or some bottleneck issues could appear in an effective data-hopping network is not properly design, deployed and maintained.

That's why a model which treats to offer a more balanced coverage in all the region while still being efficient in terms of the ratio energy harvested:energy transmitted is designed as follows.

The second moving model is designed using the edges, which defines the set of Voronoi cells, as *actors* paths. The main reason is that using those paths and considering the distance to the EP a well representative value for the subset of sensors belonging to that EP Voronoi cell, it's feasible to compute lower-cost calculations to decide which should be the energy sent by the *actors* in order to reach the EP at a certain energy level after considering the attenuation as specified in Section 4.5.

This way all the sensors which are in between the *actor* and the EP will always receive energy over the minimum threshold programmed and considering an average use of all the edges as *actors*' paths (which really only happens for some combinations of *actors* and Event points) then all the sensors will receive at a certain instant enough energy to recharge their super-capacitor.

Finally each *actor* is assigned to one of the inner vertices of the Voronoi cells and move back and forward to each of the edges that intersect their original vertex. In Figure 4.2b, the motion is showed by the bold dark line, for the rightmost vertex of the tessellation.

## 4.4 *Actors* deployment

While the moving model is mainly responsible for an efficient energy transfer and system improvement, the initial *actors* deployment has significant bearing on any result not providing a balanced coverage for all the scenario (all the *actors* in the same region, some regions overpopulated and some others starved of *actors*) will induce to a premature ending of the lifetime because of energy starving for those uncovered regions and a over-consuming rate for those overpopulated by *actors* regions. Hence, we delve into the deployment issue in detail.

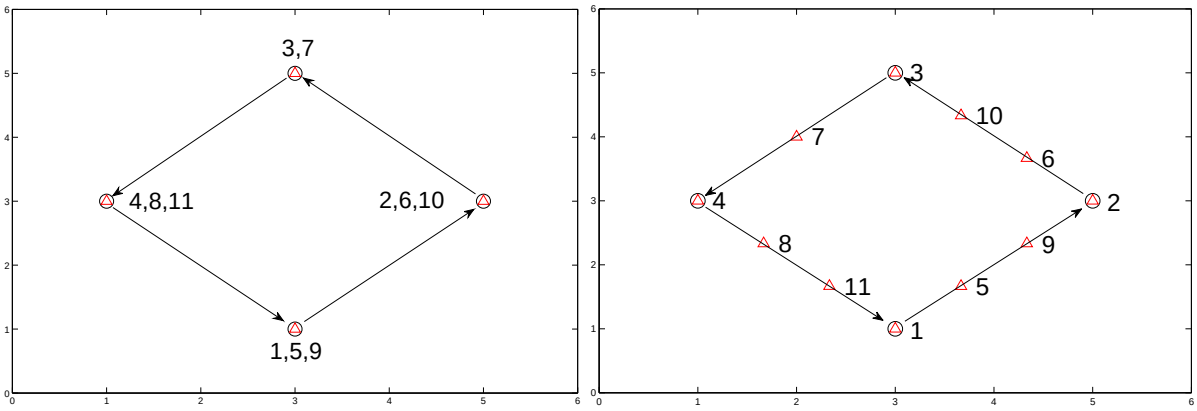
### 4.4.1 Deployment EM

For the CM mode one TSP path is created previously and the next algorithm basically deploys the sensors through that path trying to have a balanced distribution in space and time. The steps are as follows:

- *Step1:* If the number of *actors* is greater than the number of EPs, one *actor* is deployed in each EP in turns.
- *Step2:* *Step1* is repeated until the remaining number of *actors* is less than the EPs, as shown in Figure 4.3a (for a case of 4 EPs and 11 *actors*).

- *Step3:* Once all the *actors* are deployed in the EPs they are re-positioned equidistantly from each other on the path connecting two successive EPs belonging to the traversal path (see Figure 4.3b).

Thus, a final distribution is obtained maximizing the coverage constrained to the number and distribution of EP and *actors*.




(a) Starting distribution among EP

(b) Final equidistant distribution

Figure 4.3: *Actor* deployment for CM

### 4.4.2 Deployment CM

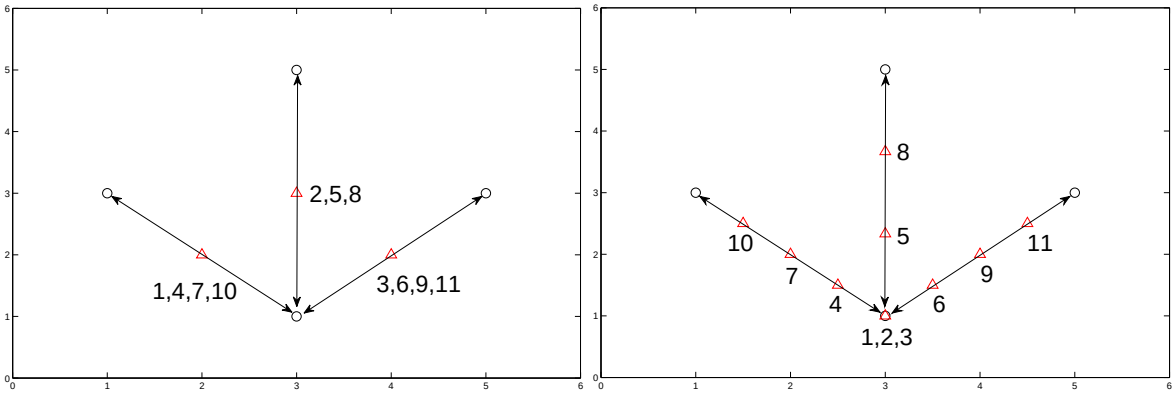
For the other mobility model (EM) the deployment method keeps the same basic lines but with some variations and an additional step. As seen in the next description here the references used are not the EP coordinates but the set of vertex where the different Vonoroi cells adjoins.

- *Step1:* If the number of *actors* is greater than the number of inner Voronoi vertices, one *actor* is deployed in each one of those vertices.

- *Step2: Step1* is repeated until the remaining number of*actors* is less than the inner corners, as seen Figure 4.4a (for an example of 4 EPs and 11 *actors*).

- *Step3:* Once all the *actors* are deployed in the corners they are redistributed in the different branches following the same method, same amount in each branch and the rest averagely distributed considering the order of branches in which all the *actors* will move through from each original EP as the one clockwise.

- *Step4:* Finally each *actor* belonging to one branch is repositioned equidistantly from each other connecting the two successive inner corners (see Figure 4.4b).




(a) Starting distribution among edges

(b) Final equidistant distribution

Figure 4.4: *Actor* deployment for EM

## 4.5 Moving *actors* and energy propagation

Finally after the deployment of the *actors* the simulation can be finally run to analyze the variations the network energy and lifetime suffers under some changes on the network parameters.

Due to the movement of the *actors* along the predetermined paths, some energy is spent on the movement. This incurs on a secondary consume of energy by *actors*, on one side the one used to transmit energy through the radio channel to the sensors and secondly the one used to move. The set of *actors* is considered to be moving at a constant speed of 2 m/s producing a consume 150 mW for each actor, derived from equation (4.2).

$$E_v(W) = 0.05\,W/(\frac{m}{s})^{\gamma}\ ,\ \ \gamma = 1.5 \tag{4.2}$$

The second energy consumed part, due to the energy sent by *actors*, highly depends on the distance from the *actor* to the closest EP. As told before, a predetermined value of energy is required by the EP to be received. Then to compute this required energy level, the Friis equation (4.3) is used.

To give an easier look to the formulas they are arranged in a different way from the original one proposed. First of all we separate the parameter we are analyzing $P_t(W)$ and consider both gains of the transmitter and receiver equals to one $G_t, G_r = 1$ obtaining equation (4.4). Then we rearrange the

division and group all the values which keep constant arriving to equation (4.5), were is easier to evaluate the dependencies with distance ($R$) and frequency ($f$).

Now with equation (4.5) we can see the squared variation of the power level required to be transmitted with both frequency (as it varies from $f = 642\,\text{MHz}$ $\lambda = 46.7\,\text{cm}$ to $f = 915\,\text{MHz}$ $\lambda = 32.8\,\text{cm}$ giving and increment of required power $\triangle_{642MHz \to 915MHz}[P_t(W)] = 2.03$) and distance. As for high distances the required power level tends to infinite, some limitation has to be applied to *actors* which is decided to be 4 W as it is the maximum power allowed to be transmitted at those frequency bands. Finally, the final power level to be transmitted is defined as seen in equation (4.6).

$$P_r(W) = P_t(W) G_t G_r (\frac{\lambda}{4\pi R})^2 \ , \ \lambda = \frac{c}{f} \tag{4.3}$$

$$P_t(W) = \frac{P_r(W)}{(\frac{\lambda}{4\pi R})^2} \quad , \ \lambda = \frac{c}{f} \tag{4.4}$$

$$P_t(W) = \frac{P_r(W)(4\pi R f)^2}{(c)^2} = k P_r(W)(Rf)^2 \quad , \quad k = (\frac{(4\pi)^2}{(c)^2}) \tag{4.5}$$

$$P_t(W) = \min(\frac{P_r(W)(4\pi R f)^2}{(c)^2}, \quad MAX_ET) \ , \ MAX_ET = 4W \tag{4.6}$$

As the signal has to be harvested by an EH circuit already designed in this same research laboratory [14] all signal which power is lower to $-20$ dBm is considered null, while over it the efficiency is taken for each power level from [14] as it can be observed in figure 4.5.

## 4.6 Data management

Once the MATLAB simulation code is set to run the simulation, some aspects have to be taken care of. As one of the parameters studied here is the lifetime, is counterproductive to have a predetermined number of steps to be simulated. Instead, the simulation starts a loop while until a certain threshold condition is compromised and a flag is active.

While using the number of sensors which super-capacitors have get totally discharged (e.g. they are no longer functional for the network as they have no energy to keep doing their sensing and data-forwarding tasks) as a threshold value can seem a good choice to evaluate the actual state of the network, it provides some confusing lectures:

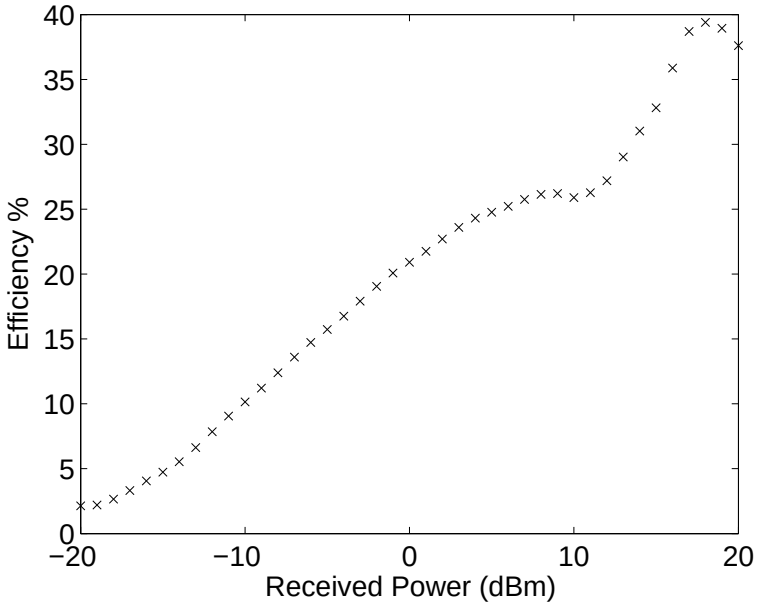



Figure 4.5: Energy Harvesting Efficiency for 915 MHz circuit

- In a certain scenario where a set of motes are placed on the outskirts of the analyzed scenario to provide some data-forwarding paths to the sink, depending on the *actors* distribution and moving mode, those outskirts placed motes won't receive enough energy to recharge the super-capacitor. This way, although all the rest sensing motes could still be working and recharging properly, the abrupt discharge rate of those data-routing motes well spread in the scenario could compromise the threshold condition comparing the whole set of sensors' energy levels and would induce to a premature ending of the simulation.

- What's more, it can always happen a different scenario, where due to a massive "event-centric" sensors deployment, a big part of the sensors will still have enough residual energy so the threshold condition flag wont be triggered. However, analyzing more accurately the scenario we could see how all the data-forwarder motes energy levels are depleted and thus no data routes to the data sinks are available, keeping the sensors sensing while not providing the results to the data sink. This case would provide a longer lifetime than the real one as it should have consider the data routes and not only the energy levels.

One easy way to avoid both previous scenarios while not having to check a bunch of parameters each loop (as it could took a high amount of time) is processing the area coverage of those motes which still

have energy to work. This way, comparing the covered data in each loop to a threshold value (set in the simulation to 50% of the coverage) we can have a reliable information of the network quality of service.

In order to calculate the coverage, each loop is checked the area covered by those still active motes as the area surrounding up to 5 m from each mote coordinates.

In order to reduce the data stored by the simulations, we only store in each loop the sum of all the energy consumed by the *actors* and also the average residual energy of the nearest of the sensors to their respective EP.

Then those simulations are repeated for each couple of parameters variations taken from Table 4.1, while the rest of parameters are set to the default value.

| **Parameter** | **Default** | **Used values** |
|---|---|---|
| Probability of consuming | $1/30$ sec | $1/\{10,20,30,40,50,60\}$ sec |
| Max TX power | 36 dBm | 36 dBm |
| Moving model | Mobile CM | Static and Mobile for EM and CM |
| No. of *actors* | 10 | 10, 20, 30, 40 |
| No. of Event points | 10 | 10, 20, 30, 40 |
| Min required power at EP | $-5$ dBm | $-20$, $-10$, 0, 5, 10 dBm |
| Harvesting Frequency | 915 MHz | 642 MHz, 915 MHz, 2.4 GHz, 5.1 GHz |
| Area | 200 $m^2$ | 150, 200, 250 $m^2$ |

Table 4.1: Parameters for the simulations

As seen in Table 4.1 the parameters studied are:

- *Probability of consuming* is the inverse of the average time between sensing slots, used to model the awake-sleep cycle of the motes.
- *Maximum Transmission power* defined in dBm is the upper boundary, as remarked in equation (4.6) used to limit the energy used by the *actors* to transmit.
- *Moving model* defines which of the four moving models specified in 4.3 is used.
- *Number of actors* is the number of *actors* chosen to be deployed in the scenario.
- *Number of Event points* used to calculate the Voronoi cells as specified in Section 4.2.

- *Minimum required power at the EP* defined in dBm is the level of power required to be received in the EP after consider the pathloss as specified in equation (4.6).
- *Harvesting frequency* is the chosen one for the EH circuits and have it's effect in equation (4.6).
- *Area of scenario* defines, in meters, the total size where sensors are deployed.

Finally once all the data is gathered, it is processed and plotted in order to show the dependencies of both energy levels (consumed and residual) and the lifetime once submitted to all the possible variations for each couple of parameter values.

# Chapter 5

# Performance Evaluation and Observations

In this chapter we proceed to analyze all the data obtained from the MATLAB simulations in order to study which are the different influences of the parameters changed and find which of the different moving models works more efficiently for the different possible scenarios.

To represent it graphically, the data is plotted for all the possible pair of parameters specified in Table 4.1 (displayed at the figures legends) and having the information of the residual energy levels in the sensors, the consumed energy by the *actors* and the lifetime (shown in Y axis) for the four different moving models (X axis) which are:

1. Static *actors* placed along the edges in the EM case (called as *static-EM*)
2. Mobile *actors* for the EM case (called as *mobile-EM*),
3. Static *actors* placed on the EPs, for the CM case (called as *static-CM*),
4. Mobile *actors* moving from one EP to another, again for the CM case (called as *mobile-CM*).

Before we begin to discuss the results it is very important to emphasize how the data was obtained during the simulation:

1. The residual energy levels for the *actors* is extracted as the average for all the cycles. This way we reduce the data analyzed (instead of having the values for all the nodes we will have just the average). Finally as different simulations will have different lifetimes, the results displayed in the figures reference to the 90% of the duration of the shortest simulation.

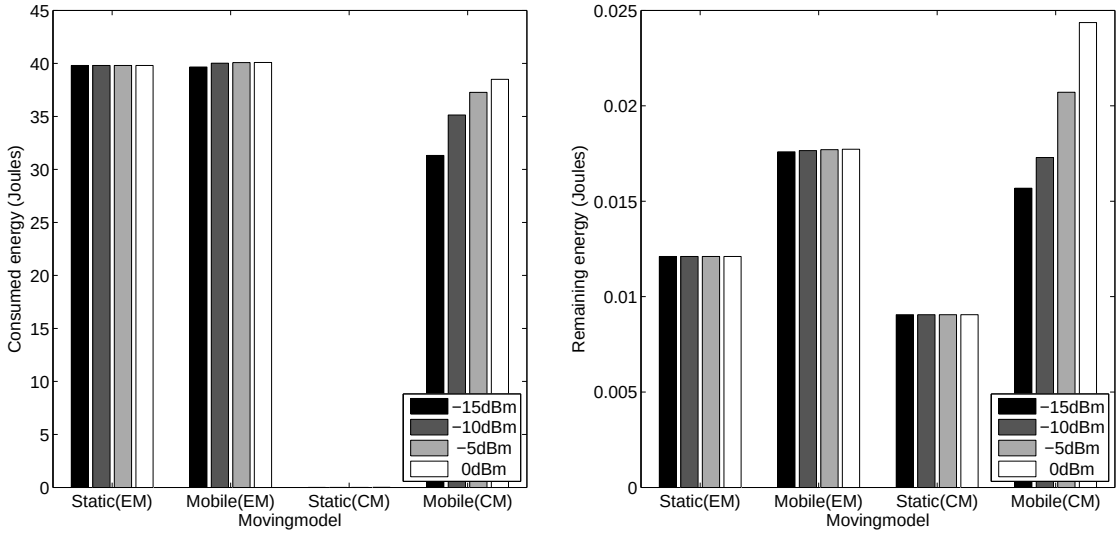
2. The consume energy for *actors* is the sum of the consume of all the *actors* in each step of the simulation. It is provided in the figures as the average over the number of steps.

3. The lifetime is the number the steps until the simulation finishes due to the condition explained on Section 4.6.

## 5.1 Minimum received power at EP

Varying this parameter we analyze how forcing the *actors* to transmit at different power levels, in order to reach the EP at a certain level after applying the Friis equation (seen in equation (4.5) which depends on distance, frequency and the requested level of power in the EP), can produce system improvements in both residual energy and lifetime (due to the non planar efficiency with the incoming power level in our experimental device) while a certain increment will be suffered in the consumed energy as well.

In Figure 5.1a the energy consumption is displayed. If we check both EM models it's easy to discover how the Mobile ones have exactly the same results than the Static ones with a constant consume added, which is the consume derived from the moving.




(a) Consumed energy

(b) Residual energy

Figure 5.1: Energy results when the minimum required power at the EP varies

Once considered it, we can observe how both Mobile EM and CM have similar results for higher

minimum received power levels in the EP while the CM consume gets more lower when we reduce the required power. This difference is produced by the attenuation (from equation (4.5)) effect.

For the EM model the Event point used to calculate the required transmission power level is always far from all the *actors* paths and then the improvement provided by increment of the minimum received power at the EP increment is countered by the influence of distance, forcing (at this frequency ranges) the *actors* to transmit always at similar power levels despite of the required ones.

Instead, with the CM as the Event points used to calculate the required transmission power level are at some points close to the EP then the Friis effect won't have any (or at least not substantial) influence over the transmission power and hence the variation displays perfectly the lineal dependence with the required power level as specified in equation (4.5).

Where we find a bigger difference is in the residual energy levels (as we can see in Figure 5.1b). We find how, due to the static overlapping position of the EP to the actors the CM static mode has the lowest consume (which is the minimal one for a certain network), then the EM static has a certain increment, independent of the reclaimed power, due to the better average coverage it is providing. With Mobile EM it appears another increment, highly independent (although not totally independent) with the required power level and finally is the Mobile CM the one that really provides a distinctive behavior with the required power level.

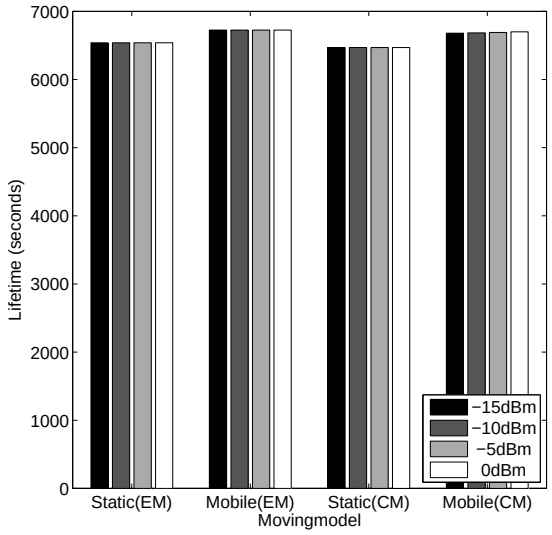



Figure 5.2: Lifetime when the minimum required power at the EP varies

Although the residual energy levels differ highly, the lifetime (see Figure 5.2) doesn't keep the same trend as all those sensors far from the *actors* routes discharge fast, and the influence of the minimum power level required at the EP only has its benefits in close range, and thus all the simulations stop in similar number of steps.

## 5.2 Frequency of transmission by *actors*

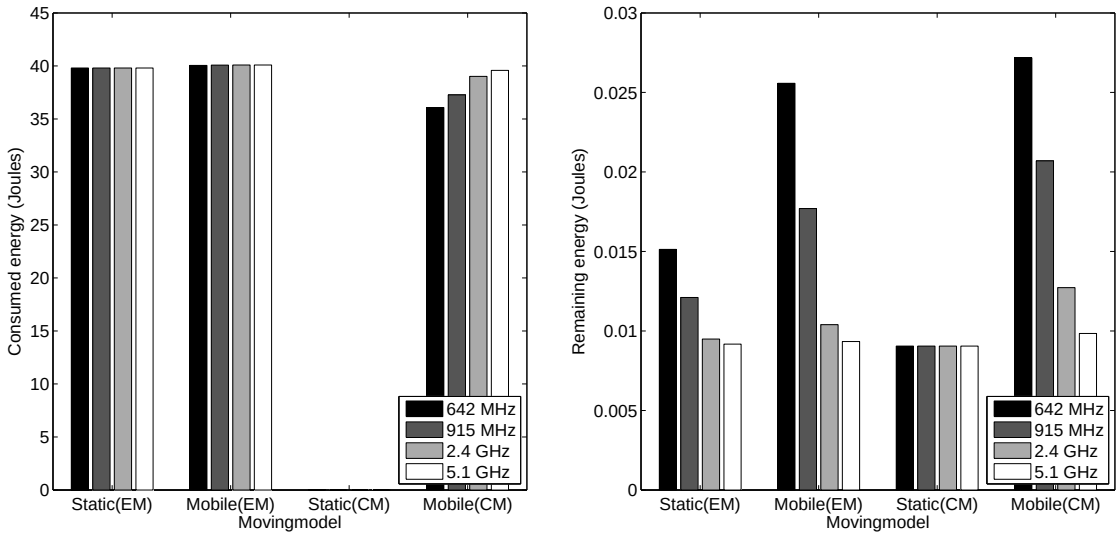
With the frequency of the signal, transmitted by the *actors* to provide energy to the sensors, we have the second parameter which is influenced by the Friis equation (see equation (4.5)). Again the dependency is the square of the frequency making it important to try to work on lower frequencies to avoid excessive attenuation.

In Figure 5.3a we can observe the variation of the consumed energy with higher frequency bands, while increasing does it with a very reduced increment. This increment is appreciable in the Mobile CM (the Static CM provides lectures close to 0Joules do the the null distance within the EP and the *actors* allowing to work always in really low bands) while in both Static and Mobile EM have constant values (the difference between the Static and the Mobile ones are due to the moving consume and they keep constant as at a middle distance the attenuation is big enough to force the emitters to transmit with the same high power level in all the possible situations).

In opposition, in Figure 5.3b we observe how the residual energy levels in the sensors suffer a bigger influence of the frequency of transmission for all the moving models. Again it is trivial to conclude that the Static CM have different results as the distance from the EP to the *actors* is null and thus the attenuation has no effect. On the other three cases (Mobile CM and both Static and Mobile EM) a system improvement is obtained for lower frequency bands respect the higher ones. In the Mobile CM case the differences are more substantial as the lower average distances EP-*actors* (and hence more attenuation dependency with the frequency) provides less attenuation even for higher bands as the 2.4 GHz one.

Analyzing the figures 5.3a and 5.3b we obtain some interesting values. On one hand when we pass from the band of 642 MHz to the band of 915 MHz the consume of power varies only a 3% so the frequency don't have a really influence in the consumed energy by the *actors*. However, when we extract data from the residual energy we obtain a very different result: from the band of 642 MHz to the band of 915 MHz the decrement of residual energy goes up to 40%.

Finally with lifetime it's easy to appreciate the influence of moving models for low frequency bands.




(a) Consumed energy

(b) Residual energy

Figure 5.3: Energy results when the minimum required power at the EP varies when the EH frequency varies

It appears a similar variation for both EM modes and for the Mobile CM while the Static CM have a constant behavior (due to the irrelevant influence of frequency when distance is null). Again the most important variation is achieved for both bands of 642 MHz and 915 MHz.

### Minimum received power and Frequency

Both parameters (minimum received power in the EP and Frequency) affects the simulation in the same way, through the path-loss formula displayed in equation (4.5). However, one does it in a lineal form (Power level) and the other in a squared one (Frequency). That's why is interesting to analyze the Figures 5.5a and 5.5b where we can observe the consume and the residual energy levels for a simulation working on the default moving model (Mobile CM) when varying both parameters at the same time. As both have a similar influence (an increment of any of them produces an increment in the consumed power and a decrement in the received power) we could expect to find a similar behavior for all the situations, which is not strictly correct as we will discuss now.

If we first analyze the low power band (at $-20$ dBm) there exists a large variation in energy consumption of *actors* for the different frequency simulations giving up to a 300% increment from the band

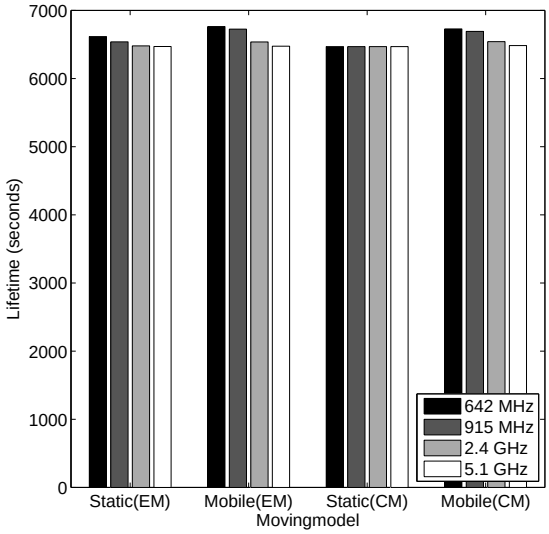


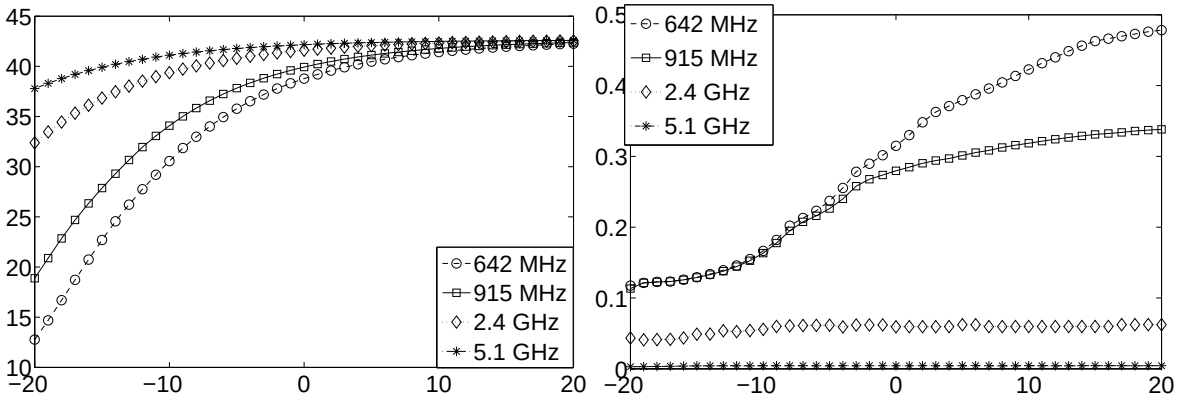

Figure 5.4: Lifetime when the EH frequency varies

of 642 MHz to the band of 5.1 GHz. The large variation in consumed energy is due to different level of effort undertaken by the *actors* to allow the sensors around the EP to receive the required power.

The residual energy levels, whilst showing a gap of energy at the final of the simulation, it is way smaller than the one obtained for high level powers because here the energy obtained depends more on the own power transmitted by *actors* than the frequency used (as the monitoring sensors are deployed in short distance to the *actors* moving paths).

Then, evaluating the high power band (around 20 dBm) though all the values suffer an increment, the trend of variation inverses. The consumed levels, which had a significant difference in the low power band asymptotically converge here to the same value as for high required power levels the attenuation have more effect and then all the *actors* will be forced to use the $MAX_ET$ power level (defined in Table 4.1 and which used is explained in equation (4.6)).

The residual energy levels, instead, suffer a bigger spread achieving differences up to 780% from 642 MHz to 2.4 GHz (when it was of 250% at the low band) showing a higher dependence of the residual levels with frequency and, hence, attenuation.




(a) Consumed energy

(b) Residual energy

Figure 5.5: Energy results when the minimum required power at the EP varies for different frequencies when the minimum required power at the EP (X axis) varies

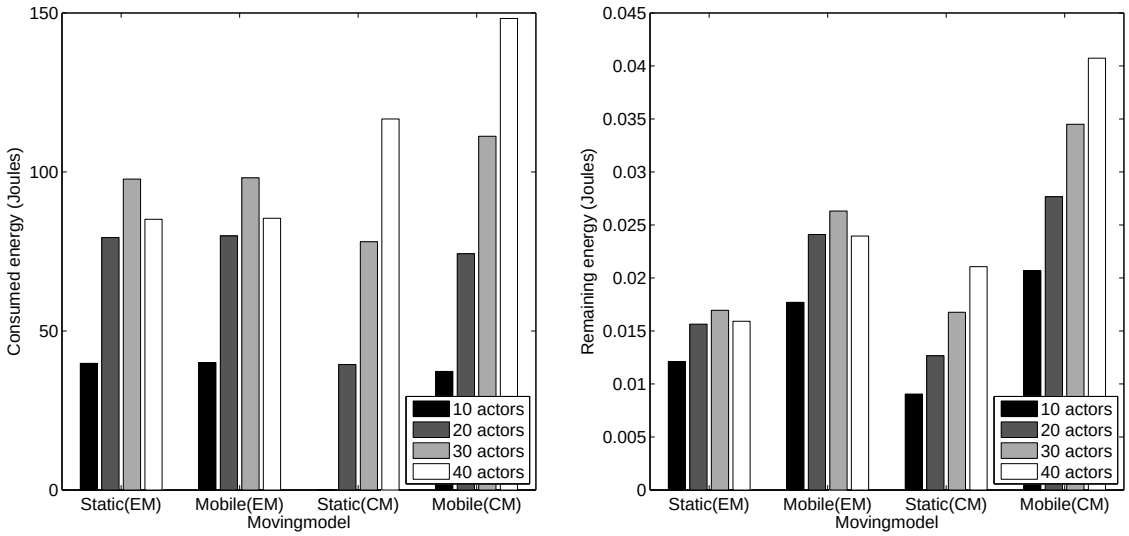
## 5.3 Number of *actors*

Just considering the theory, the number of *actors* is supposed to be related to the consume energy by *actors*, the residual energy in sensors and the lifetime in a lineal way. With more *actors*, more consume will exist as each actors' consume rate is independent of the other *actors*, more residual energy will be obtained as the power level in the energy harvesting circuits will be increased and thus the lifetime will get enlarged.

The problem with the previous hypothesis incurs in not considering the constrain of the moving models move patterns and the *actors* deployment method and hence the real energy propagation map of the scenario. As the paths doesn't cover all the region, and increasing the number of *actors* decreases the time of energy propagation cycles (meaning by cycles the period of time in between two instants where the energy levels in all the scenario are repeated) but doesn't increase the coverage in farther zones, the results are not so trivial as it seemed.

If we observe both the consumed and the residual energy levels (figures 5.6a and 5.6b respectively) we realize that the expected lineal increment is correct for the CM but for the EM modes (both Static and Mobile) the variation, while expected for the three first cases $(10, 20, 30)$ *actors* changes for the case of 40 actors. Here a decrement in both consumed and residual energy occurs due to the variations suffered by the *actors* network geometry for that specific number *actors* and Event points.

Referent to the lifetime, increasing of number of *actors* as seen in Figure 5.7 clearly improves the




(a) Consumed energy

(b) Residual energy

Figure 5.6: Energy results when the minimum required power at the EP varies when the number of *actors* varies

network lifetime. Moreover, the moving models deliver a smoother improvement compared to the static modes one. While the mobile EM presents a saturation (the increment of lifetime gets smaller with each new increment of *actors*) the inverse happens with the CM where each time the increments gets larger.

## 5.4 Number of Event Points

The aim of this parameter goes farther than just evaluating how the network behaves for a different amount of EP. As the Voronoi itself depends on the number and position of the EP, this parameter has a very important role in the setting up of a network and in the simulations.

As the variation of EP produces changes in the Voronoi cells, then, as EPs increase, on one hand the overall length of edges that the *actors* need to travel increases, while on the other hand the paths in between EP gets reduced.

Hence, because of the reduction in the average distance from *actors* paths to EP, the *actors* will require less power to achieve the same power at the EP and the global consume caused by *actors* mobile methods gets reduced, but the variation won't will suffer the counterpoint of longer periods to cover all

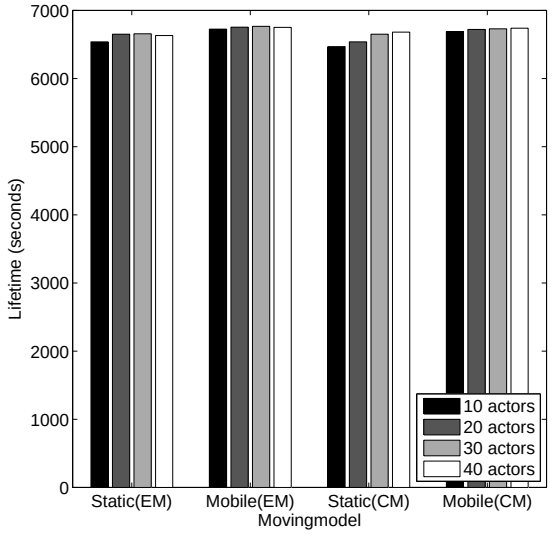



Figure 5.7: Lifetime when the number of *actors* varies

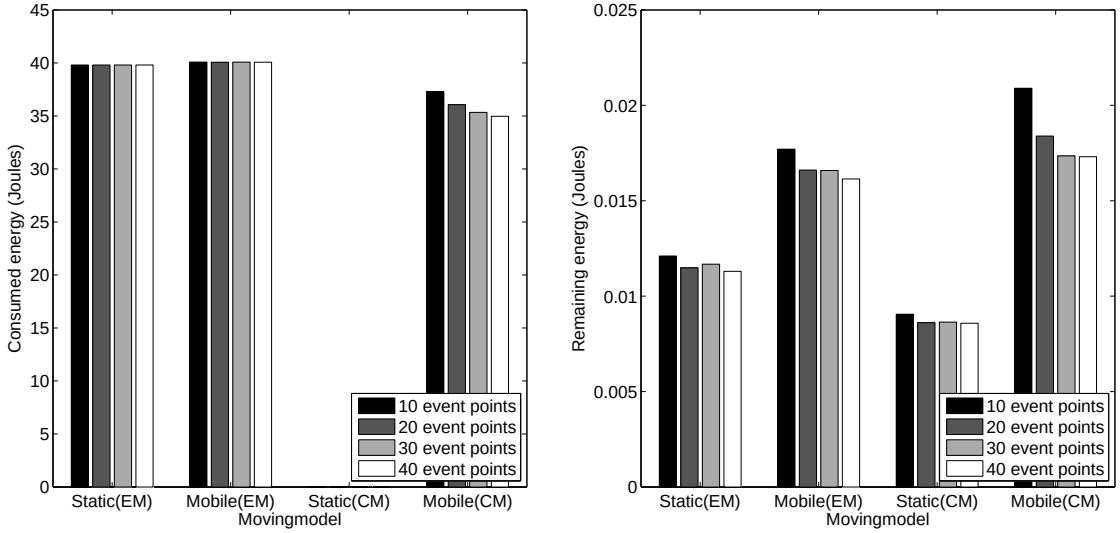
the scenario and hence a larger variation in coverage. This will induce to a slight decrement of energy consume by *actors* depending on the quantity and localization of the EP, as we can appreciate in Figure 5.8a, where for the EM there isn't an appreciable influence and for CM just a slight decrement appears forced by the averagely reduced distance for the pair *actors*-EP.

Additionally, as we can observe in Figure 5.8b, for the residual energy levels the results depends again on the distribution of the EP. When the number of Event points randomly generated for the each analyzed value is reduced, each increment will provide a big difference (cases of 10 and 20 EP) while for higher amounts of Event points (and thus a reduced relative variation on the EP quantity) the variation will be importantly reduced.

In both cases, the mobile methods provide an improvement over all the configurations but, while the static ones the improvement is always almost negligible, for the mobile ones it improves more as a consequence of the coverage enhancement provided by the moving models as there will be a more regular coverage of the area.

Remember that the number of *actors* is set to 10 independently of the number of Event Points. If both parameters were assigned together then a increment of EP would always provide an increment in both consumed and residual energy levels as the number of *actors* would be increased as well.

Figure 5.9 shows the effect of number of Event points on network lifetime. While increasing the




(a) Consumed energy

(b) Residual energy

Figure 5.8: Energy results when the minimum required power at the EP varies when varying the number of Event Points (b)

number of Event points yields an improvement in terms of energy consumption, there is a negligible improvement in network lifetime.

## 5.5 Probability of consuming by sensors

Although this parameter is set as an amount of seconds in the legend to make it easier to read, it keeps referring to the concept of probability. As explained previously in Section 4.6, in order to emulate the awake and sleep cycles on the motes while maintaining a certain randomness, on each cycle each sensor transmits with a certain $P(Tx)$ as specified in equation (5.1):

$$P(Tx) = \frac{1}{num_sec} \quad , \quad num_sec = \{10, 20, 30, 40, 50, 60\} \tag{5.1}$$

This way, on every slot each sensor will have $P(Tx)$ to transmit independently of their previous slots and the rest of the sensors.

Here we analyze how this parameter influences the network. As lowering the probability $P(Tx)$ implies more sleeping time, it will yield a decrement of the energy consumption by sensors and thus a

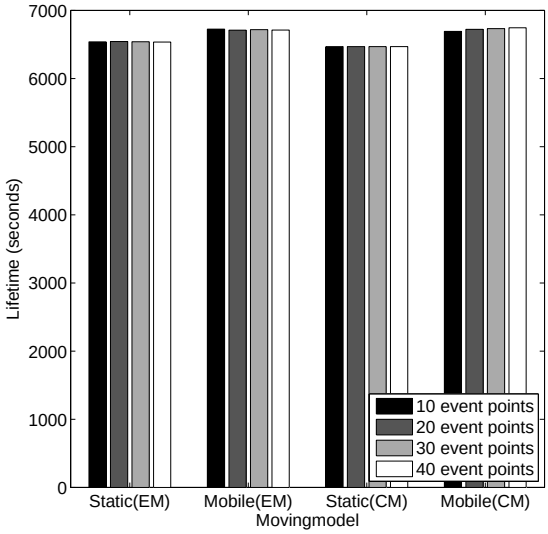



Figure 5.9: Lifetime when the number of Event points varies

increment in both the residual energy levels in the sensors and the lifetime.

Note that the consume is reduced for the sensors while the *actors*, which are independent of the sensors election of consuming or sleeping, keep consuming the same amount of energy for the different configurations of the probability of sensors consume.

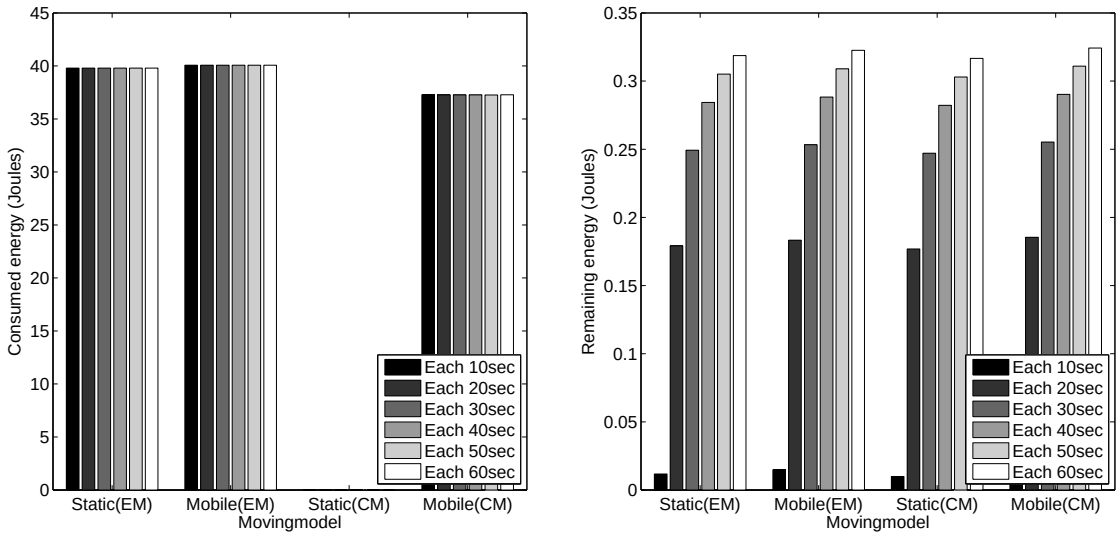
It's trivial then to evaluate how the consume of *actors*, displayed in Figure 5.10a is always constant to the different realizations while the residual energy (Figure 5.10b) and the lifetime (Figure 5.11) increase as expected with the sleep cycle getting also increased (as the probability of consume by sensors gets reduced).

Evaluating the previous information we can conclude that, when it is possible due to loose temporal sensing constraints for the sensors, increasing the sleep time will provide longer lifetime and higher residual energy levels maintaining the same energy consume by *actors*, offering a good tool to improve the network.

## 5.6 Area scenario

This parameter is set to evaluate how escalable the moving models are.

On the first versions of the simulations we decided to work with a constant number of sensors, kept to 200, to make it faster to simulate. Although at that moment, using for the simulation ending the




(a) Consumed energy

(b) Residual energy

Figure 5.10: Energy results when the minimum required power at the EP varies when varying probability of consuming by sensors (b)

percentage of sensors without energy as explained in Section 4.6, results seemed correct, then, when the simulation end criteria was changed to the coverage area, a big discharge rate happened abruptly for the whole set of sensors and the lifetime got highly shortened when the scenario was enlarged.

This abrupt discharge was induced by a big increase of the mean distance among sensors and both *actors* and EP and, thus, a sparse sensor density. Then, the probability of having a big set of sensors which energy harvesting circuits couldn't gather enough energy increased, finishing prematurely the simulation.

The solution was achieved by providing a constant density of sensors (hence a variable number of sensors) in function of the area instead of a constant value of sensors, obtaining this way comparable results for all the realizations.

In Figure 5.12a a negligible increment of consumed energy by *actors* can be appreciated in the Mobile CM while the rest keep constant for all the cases.

Nevertheless, at Figure 5.12b, which shows the residual energy of sensor, we can see how sensitive the residual levels are upon the scenario area (as it directly implies a variation in the mean distances from sensors to *actors*). Considering some values we can observe how the residual energy of sensors tends to

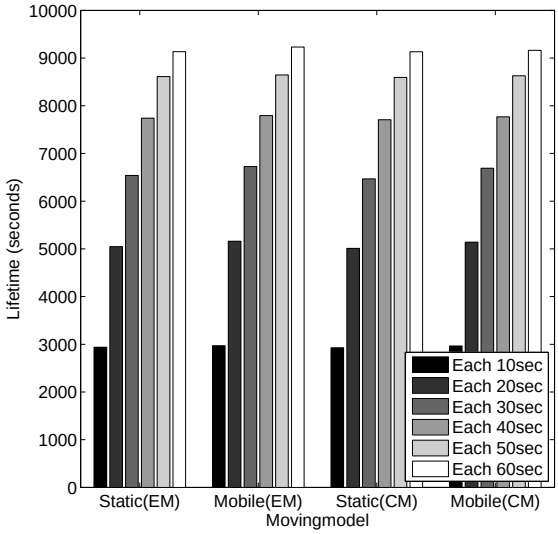
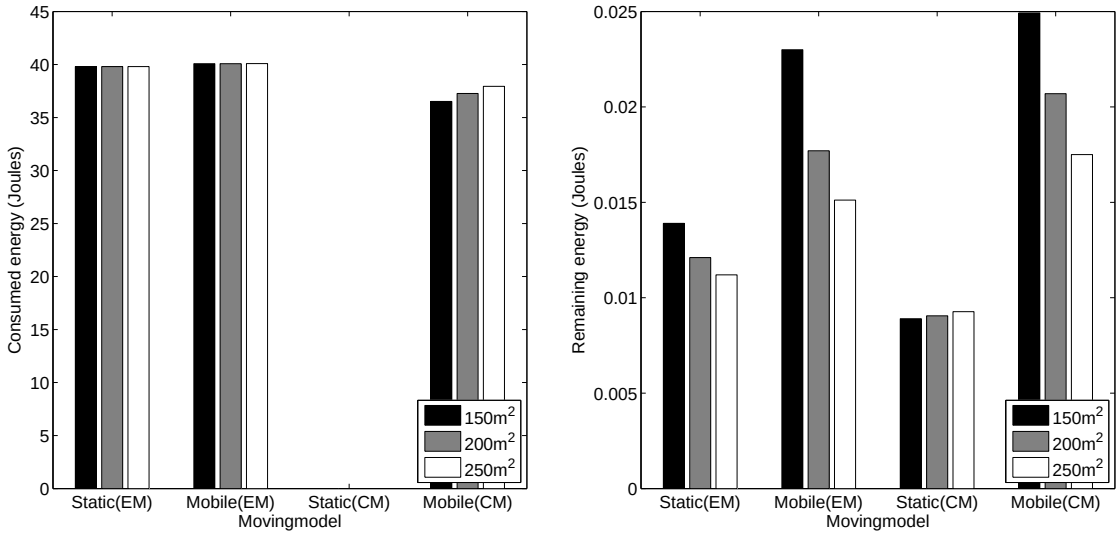



Figure 5.11: Lifetime when the seconds between sensing varies

increase up to 45% times from 250 $m^2$ to 150 $m^2$ for mobile CM and up to 50% times for mobile EM, revealing a higher sensitiveness of CM to the area of the scenario in absolute values while the EM has bigger relative improvement among its different area cases.

The lifetime, in Figure 5.13, displays the variation with the re-sizing of the scenario. It incurs in an appreciable increment of the lifetime but not as substantial as the increment of the residual energy levels. This happens, again, due to the faster discharge rate of the subset of sensors in the outskirts of the region, far from the *actors*.




(a) Consumed energy

(b) Residual energy

Figure 5.12: Energy results when the minimum required power at the EP varies when the scenario area varies

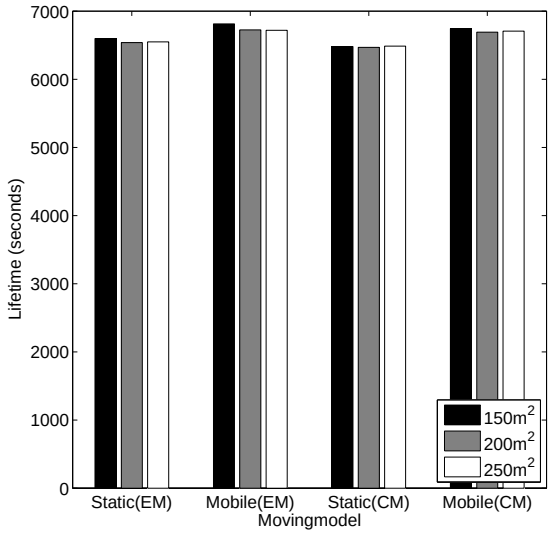



Figure 5.13: Lifetime when the area of the scenario varies

# Chapter 6

# Empirical measurements of Radio Frequency Energy Harvesting

The large scale of WSAN makes unfeasible to deploy and analyze a whole system to check the accuracy of the simulations obtained. While most of the determinant parameters of a WSAN have been considered for the simulation, one had to be excluded, the scenario attenuation variations.

The reason to exclude this parameter and use instead a basic Friis attenuation model equation is the high variation and unpredictability of the results for each possible coordinate of each scenario.

While the Friss equation provides a good solution for open space and relative high distance installation situations, where possible obstacles where the waves can rebound are far and thus the scenario can be compared to Figure 6.1, usually the situation will differ from it.

The most important obstacle, which causes at least a second wave reaching the receiver, is the ground of the scenario. While ceilings and walls are avoidable in outside scenarios, the floor, if the elements conforming the WSAN are not set at a high height, will reflect a second wave to the receiver as we can see in Figure 6.2. Here, the blue ray represents the direct path from emitter to receiver while a second ray, the orange one, rebounds in the floor and after some power lose and phase shifting reaches the receiver (red ray).

Although at first glance it can seem a productive effect on the transmission, different factors will affect the final result. The phase-shifting caused by the reflection, altogether with the total difference distance of both paths (the blue one against the sum of the orange and the red one), will induce a difference in the total phase of the two sinusoidal waves reaching the receiver. Considering $W_d$ the direct

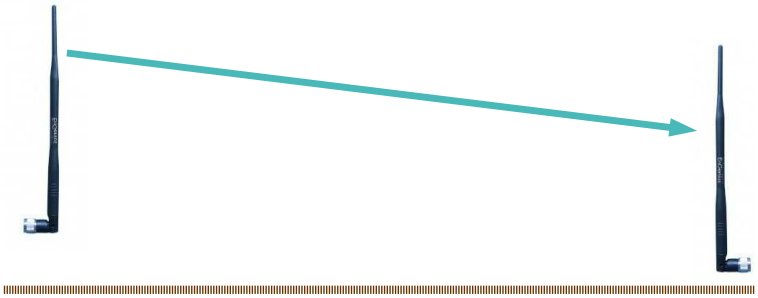


Figure 6.1: One ray model

wave, $W_r$ the reflected one we obtain the resulting wave $W_t$:

$$W_d = A * cos(\frac{2\pi}{\lambda} x_d + \varphi) * e^{-\alpha x_d} \tag{6.1}$$

$$W_r = A * \Gamma * cos(\frac{2\pi}{\lambda} x_r + \varphi + \phi_r) * e^{-\alpha x_r} \tag{6.2}$$

$$W_t = A * e^{-\alpha x_d}[cos(\frac{2\pi}{\lambda} x_d + \varphi) + \Gamma * cos(\frac{2\pi}{\lambda} x_r + \varphi + \phi_r) * e^{-\alpha(x_r - x_d)}] \tag{6.3}$$

Although the next simplifications are not always applicable to the scenarios, in order to provide a comprehensive explanation of the results of equation (6.3) we will consider them.

- $\Gamma$ express the percentage of the wave amplitude which is reflected from the surface (in this case the ground). We consider it to be equal to $\Gamma = 1$ which implies a perfect reflection without loses.
- If the difference among total distances $(x_r - x_d)$ can be negligible then $e^{-\alpha(x_r - x_d)} = 1$. It could only happen when both distances are large or both antennas are really close to the reflective surface and thus the reflecting angle is small.
- The initial phase $\varphi$ is set to zero to simply more the equation. While it has a contribution to the absolute result, it is uncorrelated to the variances with distance.

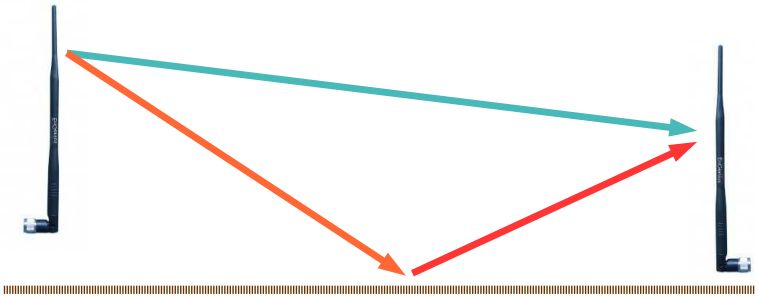


Figure 6.2: Two ray model

- Also the phase-shifting ($\phi_r$) caused by the reflection is considered null. This has influence over the result but it is required to be simplified to operate the trigonometry properly for a basic explanation.

With those approximations the new conformed wave is:

$$W_t = A * e^{-\alpha x_d}[cos(\frac{2\pi}{\lambda}x_d) + cos(\frac{2\pi}{\lambda}x_r)] \tag{6.4}$$

Where $A * e^{-\alpha x_d}$ is the amplitude of our signal after the attenuation. Considering the equation 6.5 then $W_t$ equals to:

$$cos(A) + cos(B) = 2 * [cos(\frac{A+B}{2}) * cos(\frac{A-B}{2})] \tag{6.5}$$

$$W_t = A * e^{-\alpha x_d} * 2 * [cos(\frac{2\pi}{\lambda}(x_r + x_d)) * cos(\frac{2\pi}{\lambda}(x_r - x_d))] \tag{6.6}$$

In equation 6.6 we can see the sinusoidal periodicity has changed. Specifically, now the periodicity will be shorted in half with distance, creating points of constructivity (more amplitude than in the one ray case) or destructivity (less amplitude than in the one ray case).

The effect of both phases, the initial $\varphi$ and the phase-shift $\phi_r$ will only affect in the position of those points while the effect of $\Gamma$ and the two different attenuation with distance will provoke a reduction in

both effects of constructivity and desctructivity. That's why, at bigger distances from the ground or other reflective surface or when the absorption of the surface is high, the one ray model is applicable due to the high reduction of the reflected wave influence over the final result.

Then a possible way to study the characterization of a closed room might be to consider each of the surfaces (floor, ceiling and walls) with a two ray model and then calculate the superposition. Another option, evaluated in [21] is to consider the room, specially if working in corridors or long rooms, as a waveguide.

Those techniques exceed the concept of this project while might be really useful in order to improve the system to optimize the Radio Frequency Energy Harvesting charging system.

## 6.1 Results evaluation

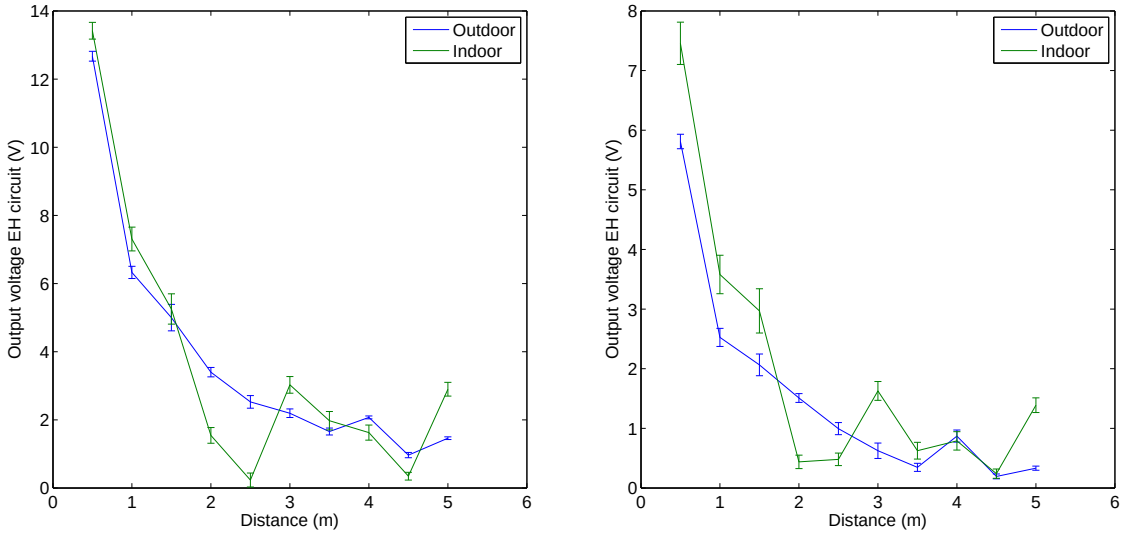
Once the effects of multiple waves have been exposed we follow to display some figures of different voltages received by our Radio Frequency Energy Harvesting circuit 1.1b on different scenarios and setups.

In all the cases the emitter has used an omnidirectional antenna and the receiver has been at 71.5 cm The variations on the setups are the next ones:

- Patch antenna on the receiver with emitter at 71.5 *mathrmcm* height.
- Omnidirectional antenna on the receiver with emitter at 71.5 cm height.
- Omnidirectional antenna on the receiver with emitter at 1.5 m height.
- Omnidirectional antenna on the receiver with emitter at 0 m height.

The voltage has been measured over ten equidistant points from 50 cm up to 5 m from the receiver, moving the emitter towards and backwards in a perpendicular path. Each experiment has been done 10 times and in the figures the mean and the confidence intervals are displayed to avoid incorrect lectures caused by human errors and punctual value dispersion.

In cases 6.3a and 6.3b where the only variation is the antenna used by the Energy Harvesting circuit to receive the power, due to a reasonable distance with the floor, the results while not perfectly shaped as expected from Friis equation, keeps a reasonable tendency.




(a) Patch antenna

(b) Omnidirectional antenna

Figure 6.3: Voltage obtained with different antennas and emitter at a height of 71.5 cm

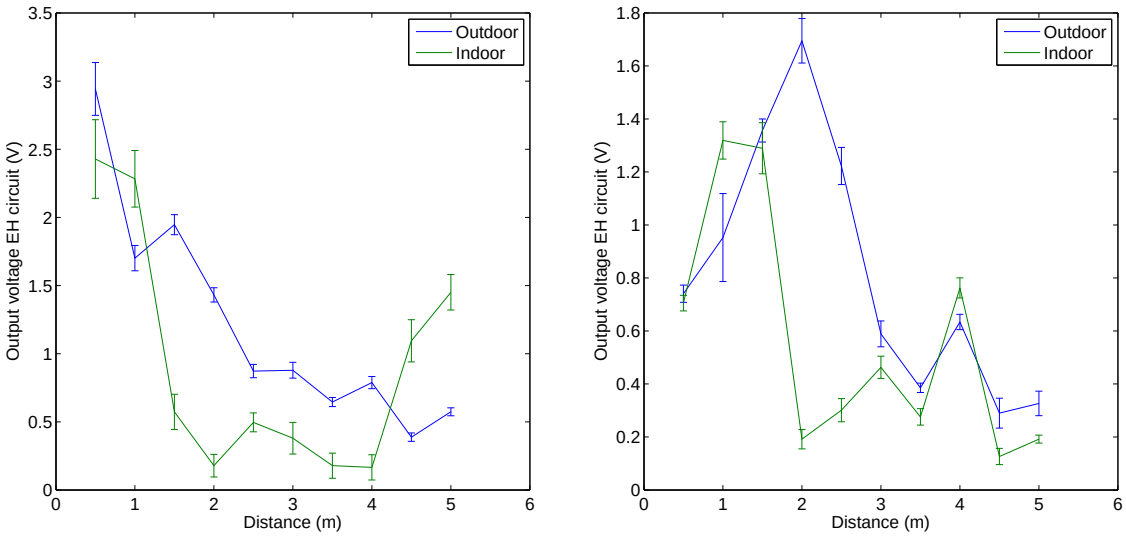
However, as we can see in both figures for short distance $(0-1.5)$ m the Indoor scenario provides an improvement, while for further situations the Indoor scenario gives us unexpected results. The Outdoor also gives a peak of efficiency caused by constructive waves at 4 m.

When the emitter's height is varied varied moving it up or down the experiment provide even more unpredictable results specially at short distances where the antenna lobe gain have a high influence on the results. That's why on figures 6.4a and 6.4b we find low mean and large confidence intervals for measurements under 2 m. Further than that, the Outdoor scenario has a predictable decreasing behavior with low peaks while the indoor shows a high increase of voltage gain in far distances compared to the middle region.

It is important to remark how this behavior depends highly with the scenario and a simple displacement of the experiment area by a meter can give low correlated results with the previous ones.

For example, in a previous experiment done in the same characterized corridor, 3 rounds of measurements where done it two locations of the same scenario, specifically moving one meter the receiver. The results for the case of a receiver with an Omnidirectional antenna and at a height of 71.5 m can be evaluated in Figure 6.5.

Here we can see how the pattern seems to have a similar trend while for a specifical point the results




(a) Emitter at a height of 1.5 m

(b) Emitter at a height of 0 m

Figure 6.4: Voltage obtained with omnidirectional antenna and emitter at different heights

are highly different, where one of the cases achieved a voltage around 2.25 Volts and the other 0.5 Volts. It might seem just a result of a high variation with time but it's trivial to check how the markers of the confidence interval displays a low variation in both experiments and thus a high reliability of the results.

With those results it's easy to comprehend how important a high detailed scenario analysis is required for a proper efficiency on Energy Harvesting charging systems where signals are low by itself and any problem with the reflections might cancel totally the function of the system.

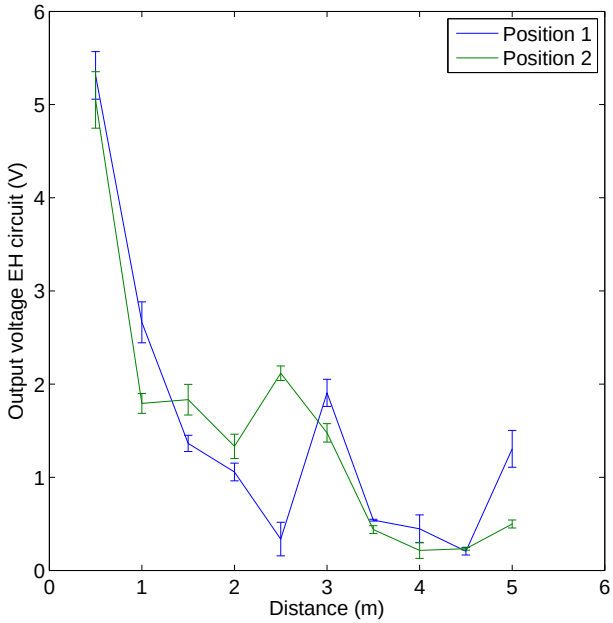



Figure 6.5: Variations of received voltage with distance in different locations of a same scenario (closed corridor)

# Chapter 7

# Open Issues and Conclusions

The Wireless Sensors and *Actors* Networks, despite of some similarities to other kind of communication networks, have some special constraints related to the energy consumption. Due to their wireless capabilities, the energy storage is drastically limited and thus the consume has to be controlled to reach a profitable efficiency in consume and energy saving.

On the last years Energy Harvesting technology has been applied to this kind of networks to provide the sensors, which constitutes the network, a way to gather energy by themselves and, hence, to obtain more autonomy. Whereas this solution itself incurs on a improvement of the lifetime while reducing the dependence on batteries, usually the sources where the energy is gather from (sun, wind, water streams) can be unpredictable and not strong enough to be the motes' exclusive energy source. That's the reason why the Energy Harvesting circuits are only being applied to low-consume circuitry.

While some other works have analyzed how to improve the energy harvesting systems using different sources as [22], we have implemented a new element in those networks, called emitting *actors*, which move through the scenario emitting radio frequency waves and providing an energy density in the scenario enough to recharge the motes through radio frequency energy harvesting, using our previously developed harvesting circuits [14] for MICA2 motes.

Once all the theory has been explained (see Chapter 4) and the results obtained from the simulations have been displayed and analyzed (see Chapter 5), some conclusions are discussed here about the results obtained.

Even considering the increment of energy consume by the *actors*, in general the results are, as expected, improving both the residual levels of energy in the sensors and the network lifetime. However, depending on the different configuration of the networks, one or the other models defined (EM and CM

as specified in Section 4.3) will be more appropriate as we summarize now:

- As all the simulations are specified for the efficiency values obtained from a previous work, with a radio frequency energy harvesting circuit, the maximum global efficiency is achieved at 0dBm. This variation is easier to appreciate in CM mode due to the higher variability of distance while, in EM, as the distance keeps a more averaged value, a more constant behavior is reflected in the results. Then a judicious selection of the required power level at the Event points can signify a drastic difference in residual energy levels and lifetime (e.g., In CM for a variation of 5 dBm in the minimum required power for recharging, the percentage increase in the storage energy goes up to 20% for the entire network).

- Referent to the frequency bands, it has been specified in equation (4.5) the relation of the path-loss (and thus the increment of required power transmission level for a certain power received threshold) with frequency, providing more auspicious results with the decrement of the frequency value. This effect, more pronounced for the moving cases, provides a high reduction in energy consumption while improving the lifetime of the network and the residual energy levels in the sensors. Importantly, there is a large difference (e.g., 50% when using the EM case) in the residual energy levels of sensors when using lower frequencies (working around 600 MHz instead of 900 MHz). As the low frequency bands are not freely available due to the uses they provide for different kinds of communications, one of the open issues to deal with might be the analysis of the availability of the different low frequency bands and the feasibility of energy harvesting circuits for those bands as the components changes, to adapt the resonance of the filters and the load adaptation with the chosen frequency.

- The variation of the number of energy transferring *actors* has influence in the different moving models simulations but it is not directly lineal at all. While in the CM, due to the always forward movement path designed, the behavior is certainty the expected one, for the EM mode the results highly depends on the geometric position of the Event points as the forth and backward movement of the *actors* can be a good way to cover the whole scenario or just some limited regions depending on the Voronoi cells distribution. The next issue to study in this aspect would be the proper generation of the Voronoi cells in order to maximize the coverage for the Mobile EM moving model.

- The emulation of the awake and sleep cycles, through the probability of each sensor to consume

in each slot, reflects a large increase of the network lifetime for all the moving models. For e.g., a variation from 20 to 30 seconds in the mean time between consuming cycles implies an increase of 38% in the residual energy level, and 30% improvement in the lifetime, while maintaining a constant energy consumption ratio. Then it should be analyzed which could be a good crossover value to maximize the lifetime and energy values (the larger the sleep time is the bigger increment we get) while maintaining an accurate event sensing freshness (as events have to be monitored every certain time to have correct information).

- The area of the scenario, used during the simulation to evaluate the effects of area scaling, displays how its variation implies a greater influence in CM residual energy level rather than EM owing to the way the *actors* move (resulting with almost double savings on the residual energy). In CM, they only move between events, i.e., from one EP to another. In EM they move around edges providing, when the distribution of Event Points is averagely spread through the scenario, a better coverage for transferring (especially to the sensors in the far fringes of the network) in larger deployment scenarios.

Finally we conclude with the general assessment that the CM provides better performance in small deployment scenarios due to it's event-centric *actors* paths, even improving with scenarios where sensors deployment distribution density is increased near to the Event Points. The EM provides better results on large deployment scenarios where the sensor density is lower and the events are scattered, having a higher distance between them. Even though, for a more efficient deployment an extensive scenario attenuation pattern study, extensively exposed in Chapter 6 might be developed.

# Appendix A

# Acronyms

**CM** - **C**enter to center moving **M**odel

**EP** - **E**vent **P**oint

**EH** - **E**nergy **H**arvesting

**EM** - Around **E**dges moving **M**odel

**TSP-GA** - **Travel** **S**alesman **P**roblem **G**enetic **A**lgorithm

**RF** - **R**adio **F**requency

**WSAN** - **W**ireless **S**ensor and **A**ctor **N**etwork

**WSN** -**W**ireless **S**ensor **N**etwork

# Bibliography

[1] S. Basagni, A. Carosi, C. Petrioli, and C.A. Phillips. Moving multiple sinks through wireless sensor networks for lifetime maximization. In *Mobile Ad Hoc and Sensor Systems, 2008. MASS 2008. 5th IEEE International Conference on*, 2008.

[2] R. Bista, Hye-Kyeom Yoo, and Jae-Woo Chang. A new sensitive data aggregation scheme for protecting integrity in wireless sensor networks. In *Computer and Information Technology (CIT), 2010 IEEE 10th International Conference on*, 2010.

[3] A. Hernandez Coarasa, P. Nintanavongsa, and K. R. Chowdhury. Impact of mobile transmitter sources on radio frequency energy harvesting. In *Globecom 2012 - Symposium on Selected Areas in Communications (GC12 SAC)*, 2012.

[4] T. Huang, P. Lu, and Chi H. Time-slot allocation for increasing the energy-efficiency of multi-hop layered wsn. In *Intelligent Computing and Integrated Systems (ICISS), 2010 International Conference on*, 2010.

[5] CRC Press LLC J o'Rourke. *Computational geometry in C*. Cambridge University Press, 1998.

[6] J. Kirk. Traveling salesman problem - genetic algorithm. http://www.mathworks.com/matlabcentral/fileexchange/13680-traveling-salesman-problem-genetic-algorithm, November 2007.

[7] R. Kusumoto. http://techon.nikkeibp.co.jp/article/HONSHI/20101021/186688/.

[8] H. Le, N. Fong, and H.C. Luong. Rf energy harvesting circuit with on-chip antenna for biomedical applications. *Communications and Electronics (ICCE), 2010 Third International Conference on*, 1:115 – 117, 2010.

[9] K. Lin, J. Yu, J. Hsu, S. Zahedi, D. Lee, J. Friedman, A. Kansal, V. Raghunathan, and M. Srivastava. Heliomote: enabling long-lived sensor networks through solar energy harvesting. *Proceedings of the 3rd international conference on Embedded networked sensor systems*, 1:309–309, 2005.

[10] Mi M., M.H. Mickle, C. Capelli, and H. Swift. Rf energy harvesting with multiple antennas in the same space. *Antennas and Propagation Magazine, IEEE*, 47:100 – 106, 2005.

[11] M. Ma and Y. Yang. Data gathering in wireless sensor networks with mobile collectors. In *Parallel and Distributed Processing, 2008. IPDPS 2008. IEEE International Symposium on*, 2008.

[12] T. Melodia, D. Pompili, and I.F. Akyldiz. Handling mobility in wireless sensor and actor networks. *Mobile Computing, IEEE Transactions on*, 9:160 – 173, 2010.

[13] J. Nikodem, R. Klempous, M. Nikodem, and Z. Chaczko. Multi-hop and directed routing based on neighborhood cooperation in wsn. In *Intelligent Engineering Systems (INES), 2011 15th IEEE International Conference on*, 2011.

[14] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury. Design optimization and implementation for rf energy harvesting circuits. *Emerging and Selected Topics in Circuits and Systems, IEEE Journal on*, PP:1, 2012.

[15] G.K. Ottman, H.F. Hofmann, A.C. Bhatt, and G.A. Lesieutre. Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. *Power Electronics, IEEE Transactions on*, 7:669 – 676, 2002.

[16] J.A. Paradiso and T. Starner. Energy scavenging for mobile and wireless electronics. *Pervasive Computing, IEEE.*, 4:18 – 27, 2005.

[17] X. Shao, B. Li, N. Shahshahan, N. Goldsman, T.S. Salter, and G.M. Metze. A planar dual-band antenna design for rf energy harvesting applications. *Semiconductor Device Research Symposium (ISDRS), 2011 International*, 1:1 – 2, 2011.

[18] A. Sofia and S. Arockiasamy. A generalized framework for energy conservation in wireless sensor network. *International Journal of Computer Science Issues*, 8:253–256, 2011.

[19] M.K. Stojcev, M.R. Kosanovic, and L.R. Golubovic. Power management and energy harvesting techniques for wireless sensor nodes. In *Telecommunication in Modern Satellite, Cable, and Broadcasting Services, 2009. TELSIKS '09. 9th International Conference on*, 2009.

[20] S. Sudevalayam and P. Kulkarni. Energy harvesting sensor nodes: Survey and implications. In *Communications Surveys & Tutorials, IEEE*, 2011.

[21] Z. Sun and F. I. Akyildiz. Channel modeling and analysis for wireless networks in underground mines and road tunnels. *IEEE Transactions on Communications*, 58:1758–1768, 2010.

[22] J. Ventura Jaume and K. R. Chowdhury. Markov modeling of energy harvesting body sensor networks. In *22nd International Symposium on Personal, Indoor and Mobile Radio Communications*, 2011.

[23] M. Weimer, T. Paing, and Z. Zane. Remote area wind energy harvesting for low-power autonomous sensors. In *Power Electronics Specialists Conference, 2006. PESC '06. 37th IEEE*, 2006.