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MASTER THESIS

The deployment of extra relay nodes around the sink in order to solve the energy imbalanced problem in Wireless Sensor Networks

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Declaration of Authorship

I, Hanz Rodríguez Ramos, declare that this thesis titled, “The deployment of extra relay nodes around the sink in order to solve the energy imbalanced problem in Wireless Sensor Networks” and the work presented in it are my own. I confirm that:

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Abstract

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Master in Innovation and Research in Informatics

The deployment of extra relay nodes around the sink in order to solve the energy imbalanced problem in Wireless Sensor Networks

by Hanz Rodríguez Ramos

Wireless sensor networks are an emerging technology that has recently gained attention for their potential use in many applications such disaster management, combat field reconnaissance, border protection, object localization, harbors, coal mines, and so on.

Sensors in these kind of applications are expected to be remotely deployed and to operate autonomously in unattended environments.

Since sensors typically operate on batteries and are often deployed in harsh environment where human operators cannot access them easily, much of the research on wireless sensor networks has focused on the energy depletion in order to achieve energy efficiency to extend the network lifetime.

In multihop wireless networks that are often characterized by many to one traffic patterns, it is very common to find problems related to energy depletion. Along the network, sensors experiment different traffic intensities and energy depletion rates. Usually, the sensors near the sink tend to deplete their energy sooner because they act as data originators and data relayers and are required to forward a large amount of traffic of the most remote sensors to the sink while the sensors located in the periphery of the network remain much of the time inactive.

Therefore, these sensors located close to the sink tend to die early, leaving areas of the network completely disconnected from the sink reducing the functional network lifetime.

In order to achieve equal power consumption at different levels of our network, we have decided to add extra relay nodes to reduce and balance the traffic load that normal nodes have to carry. As mentioned above, each level within the network faces a different amount of traffic, which becomes more intense as we approach the interior levels. This behavior causes that the external nodes, with less traffic to handle, stay more time at rest while the nodes in the inner rings face a great amount of traffic which forces them to be more active, generating a more accelerated exhaustion, reason why nodes located in the inner rings exhaust its battery faster causing the lifetime of the network to come to an end.

This work presents a comprehensive analysis on the maximum achievable sensor network lifetime for different deployment strategies (linear, quadratic, and exponential) in order to equalize the energy consumption rates of all nodes. More specifically the deployment of extra relay nodes around the sink in order to solve the energy imbalanced problem and guarantee that all nodes have balanced energy consumption and die almost at the same time.

Acknowledgements

To God, for having allowed me to reach this point and to have given me the opportunity to live this experience in Barcelona where along this adventure, I met, many wonderful people.

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*To my parents, Juan and Socorro, my sisters Annel,
Anahi and Dianey who are always in my thoughts…*

Chapter 1

Introduction

1.1 Wireless sensor networks

A typical wireless sensor network, shown in Fig. 6.7, consists of a large number of distributed detection stations called sensor nodes, with the ability of recording and monitoring many different conditions such as temperature, humidity, pressure, wind direction and speed, illumination intensity, vibration intensity, sound intensity, power-line voltage, chemical concentrations, pollutant levels and vital body functions.

These sensors are equipped with wireless interfaces with which they can communicate with one another to form a network. This self-organized infrastructure uses a multi-hop routing to deliver the collected information to some collection center commonly called sink.

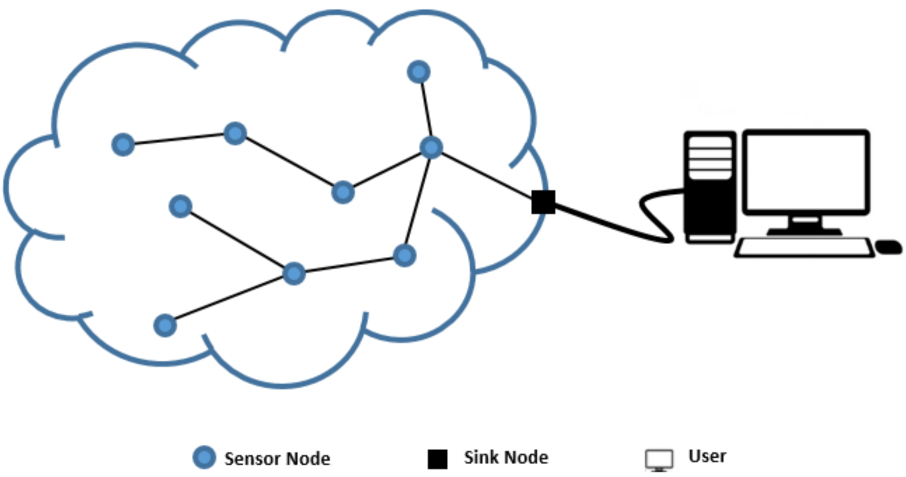


FIGURE 1.1: Typical Wireless Sensor Network.

Thanks to the rapid progresses in computer science, wireless communication, Micro Electro Mechanical systems (MEMS) and Internet, the development of sensors that are smaller, cheaper, and intelligent has been possible, giving WSN the chance to use all their potential in many applications. The design of a WSN depends significantly on the application, and it must consider factors such as the environment, the application's design objectives, cost, hardware, and system constraints. Sensors in these kind of applications are expected to be remotely deployed and to operate autonomously in unattended environments.

However sensor nodes in the network typically face severe computation and communication constraints but principally the energy depletion problem. Its own nature of be a self-organized infrastructure that uses multi-hop routing to deliver the collected information to the sink, is its main disadvantage. In multihop wireless networks that are often characterized by many to one traffic patterns, it is very common to find problems related to energy depletion. Along the network, sensors experiment different traffic intensities and energy depletion rates. Usually, the sensors near the sink tend to deplete their energy sooner because they act as data originators and data relayers and are required to forward a large amount of traffic of the most remote sensors to the sink while the sensors located in the periphery of the network remain much of the time inactive.

Sensors typically operate on batteries and are often deployed in harsh environment where human operators cannot access them easily, making it difficult or impossible to replace the batteries, that is why much of the research on wireless sensor networks has focused on the energy depletion in order to achieve energy efficiency to extend the network lifetime.

However, the challenge is not only reducing the power consumption of each sensor o increase the number of sensors near to the sink but also maintain a balance of energy consumption in the network, that is the key to prevent that certain nodes do not die much earlier than others, leading to unmonitored areas in the network.

So, maintaining a correct operation of the network is a fundamental objective. However, the resource constrained nature of sensor nodes and the network, often propose non-conventional challenges and motivate the need for special techniques for the correct design and management of WSN.

1.2 Motivation

Energy consumption is a challenge in wireless sensor network applications because the energy of nodes is highly limited and difficult to be replenished and mainly because these applications need to operate for a long time. For example, habitat monitoring may require continuous operation for months, and monitoring civil structures requires an operational lifetime of several years.

The lifetime of a sensor network has several definitions in the literature. Some researchers consider the end of its lifetime when a node runs out energy, in other words is the time when the system starts operation until the time when the first node exhausts its energy. Due to sensors nodes define the lifetime of the whole network, energy consumption has to be carefully balanced among them.

So, finding some distribution that allows a correct energy balance, is the main topic of this work.

1.3 Goals

In the field of WNS, more specific, in applications where the many to one traffic pattern is required, multihop forwarding may cause energy imbalance as all the traffic must be routed from the external nodes to the sink, creating a hot spot around the base station or commonly called sink.

Despite the fact that many node distribution strategies has been considered in the literature, where the node density in regions closer to the sink is increased, in order to face the increasing traffic rate in those regions. There is no general framework to evaluate what is the best strategy that allow to achieve the maximum lifetime of the network. In other words, there is no easy way to compare the advantages and disadvantages of these various deployment strategies.

This work address the network energy balance problem and analyze the limits of network lifetime for different deployment distributions.

More specifically, this work proposes the deployment of extra relay nodes around the sink in order to solve the energy imbalanced problem. Through extensive simulations using different distributions the objective is to find an efficient way to adjust the density of relay nodes in order to guarantee that all nodes have balanced energy consumption and die almost at the same time.

Chapter 2

State of the art

In this chapter, we introduce the state of the art involving the most common challenges related to WSN with the objective to let the reader know a general idea of how this area has been evolved and to highlight the different efforts to solve these issues.

As we mentioned, several researchers have studied and addressed the most common challenges involved in the study of WSN. In this chapter we classified the related work into three categories: the energy hole problem, the node distribution strategies, this work mainly focus on it, and the energy efficient design.

2.1 The energy hole problem

Various schemes have been proposed to address the energy hole problem. It has been shown analytically in [13] that the energy hole problem really exists in various sensor networks and in [15] the authors proved that the energy hole problem is inevitable under certain conditions. They also assume that the nodes are distributed uniformly in the network and report data constantly.

So, the energy hole is most common observed in networks where all the nodes are homogeneous and are deployed uniformly and need to send the data at constant rate to the sink. Since the entire network traffic flows toward the sink, the sensor nodes located in the periphery of the network need to send the sensing data to the sink. Due to the nature of the topology of the network, the traffic follows a many to one pattern, some sensor nodes far from the sink cannot send their data directly the sink and need other nodes to relay their data to the sink node. As a result, their energy consumption rates tend to be higher than those nodes that are far away from the sink because the nodes close the sink have to spend much energy to send their own data and relay the data sent by the far nodes, therefore, dying faster.

When the nodes close to the sink all die, no data can be sent to the sink and the sensor network stops working, leaving a hole near the sink and partitioning the whole network while many remaining nodes, commonly the nodes in the periphery, still have a plenty of energy Fig. 2.1. This phenomenon is called the energy whole problem and when it appears no more data can be delivered to the sink. That phenomenon occur because sensor networks often experience unbalanced traffic distribution which causes a considerable amount of energy is wasted, and the network lifetime ends prematurely.

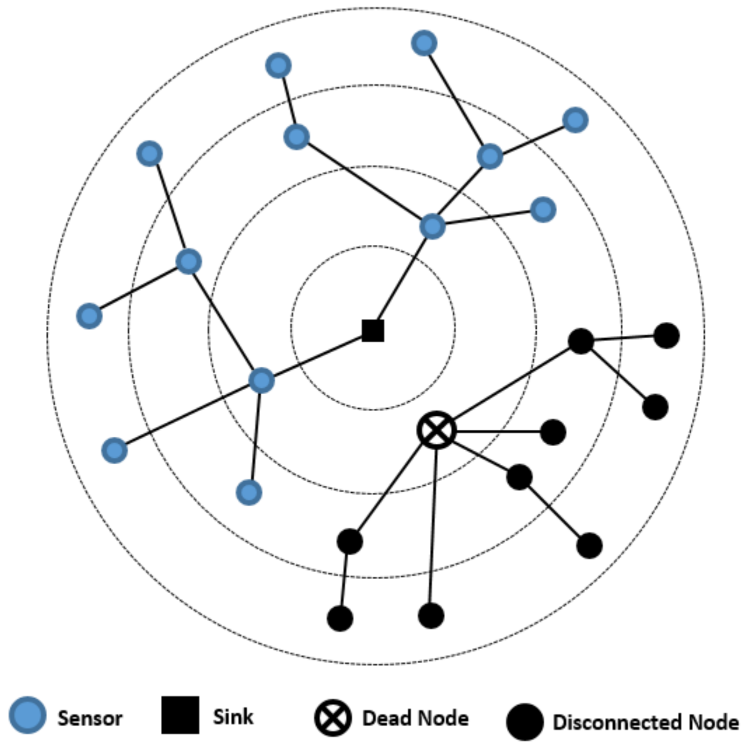


FIGURE 2.1: The energy hole problem.

Several studies have proved that when a node close to the sink runs out of energy, the remaining nodes have plenty of energy. Experimental results in [14] show that using a normal uniform deployment, up to 90 percent of the energy of the network can be left unused when the network lifetime is over. Likewise, in [15], the authors claimed that when the nodes one hop away from the sink use up all their energy, the remaining nodes have used only 7 percent of their energy on average.

2.2 The node distribution strategies

The main goal in sensor deployment is to determine the location of the sensor nodes that minimizes the cost, provides high coverage and resilience to failures, and notably prevent energy hole. Due to the multi-hop many to one traffic pattern typical in WSNs, the network often experiences unbalanced traffic distribution where sensor nodes act as data originators and relay nodes. In this case authors in [21] proved that an energy consumption rate is unavoidable if all the nodes in the network are homogeneous and are deployed uniformly in the network.

In order to solve this issue, authors claim that by carefully increasing the number of nodes around the sink, they can prevent the sensor nodes near the sink from depleting their energy faster than others, and hence, resolve the energy hole problem. For example in [21] the author proved that completely balanced energy consumption among all the nodes is impossible due to the own nature many-to-one traffic pattern in WSNs. Nevertheless, the balanced energy consumption in the network is still achievable but only if the number of nodes grows in geometric progression from the outer coronas to the inner ones except in the periphery of the network

Of course, adding more nodes to the areas with heavier traffic, especially in the area closer to the sink, is a natural way to mitigate the energy hole problem, also has other benefits, such as better connectivity and higher reliability, thus creating different node densities in different areas in the network. This is what is called non uniform node distribution. But the drawback of these solutions is that they considerably increase the number of nodes around the sink, which consequently increases the deployment cost. Therefore this solution is only effective in situations where inexpensive sensors can be mass-produced or in places where human operators can access them easily to add more nodes. Recent advances in micro-electro-mechanical and integration technologies make the first situation, cheaper nodes, more and more likely to occur.

Different studies using a non-uniform deployment have been presented in [21, 22, 23, 5, 1], where the node density in regions closer to the sink is increased progressively to deal with the increasing of traffic in those regions. The deployment of extra pure relay nodes around the sink can also be helpful in solving energy imbalanced problem [23, 18].

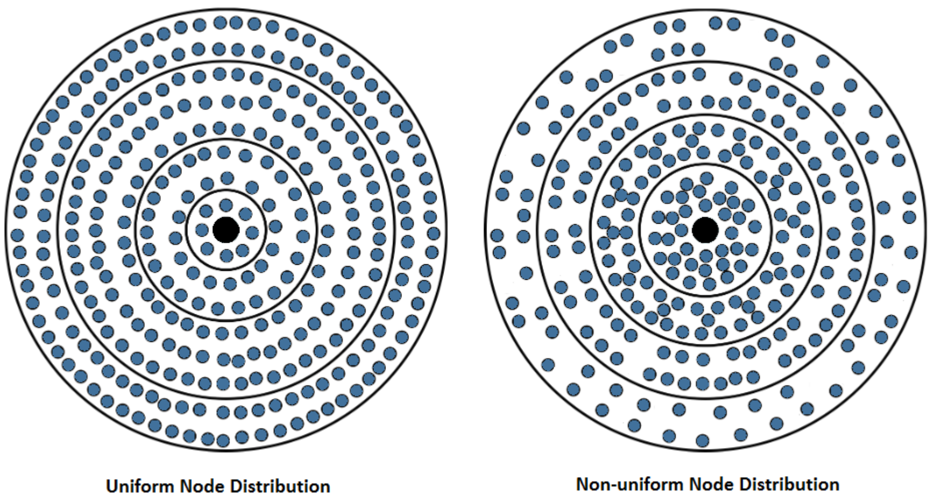


FIGURE 2.2: Uniform distribution vs Non-uniform distribution.

2.3 The energy efficient design

Energy consumption is the bottleneck of wireless sensor networks because the energy of nodes is highly limited and difficult to be replenished for example a node is considered dead when it runs out energy. So energy consumption has to be carefully considered for sensor nodes.

The objective of energy management is to increase network operational lifetime through energy efficient protocols (Routing, MAC, etc.), for example, in [9], it show how energy consumption can be balanced by distributing packets over several paths.

To accomplish this goal of lifetime maximization, the load balancing using a combination of intelligent routing and transmission power control has been studied for many researchers; In [4], authors show how the optimal combination of several routing costs allows to extend the network lifetime, in [19] different heuristic routing costs were recommended for use in order to minimize and balance the energy consumption and the problem of finding the optimal routing path to achieve the maximum network lifetime in a sensor network was studied as a constrained linear program optimization in [2, 17], and [24].

In [20] the energy hole problem is discussed, again, in WSNs with non uniform node distribution. They assume that the data rates of the nodes are tunable and only consider the energy dissipation in data transmission. The authors observed that balanced energy consumption is possible when the data rates are adjusted. The researchers in [21] study the same issue by adopting a more practical energy model that incorporates the energy spent in both data transmission and reception with the assumption that all the nodes constantly report data to the sink. They propose q-Switch Routing, a distributed shortest path routing algorithm adapted for the proposed non uniform node distribution strategy. It effectively switches the data flow among its corresponding next-hop forwarding candidates in order to balance energy dissipation among them.

Other studies have addressed the energy consumption problem by carefully placing more sink nodes over the network. In [1] authors claim that the location of the sink also can influence the network performance.

They opt to categorize the various strategies for statically positioning single and multiple sink in WSN, with the objective to help application designers identify alternative solutions and select appropriate strategies to determine the location of the sink.

In that work they highlight the potential of careful positioning of the sink and introduce dynamic schemes that reposition the sink during the network operation. They show that dynamic sink positioning can be very effective in optimizing the network functional and non-functional performance objectives in order to face dynamic changes in the environment and available network resources. In addition they argue that dynamically positioning the sink while the network is operational can be a very effective means for boosting the dependability attributes of the network. How ever since optimal sink positioning in WSN has proved to be NP-complete [8], several heuristics were proposed to find sub-optimal solutions [8, 3, 16].

The deployment of extra relay nodes around the data sink can also be helpful in solving energy imbalance problems. In [6], autors define the relay nodes as simple energy deposits. In their work, they present the optimal energy distribution map for the network which is used to determine the areas where energy is insufficient and thus determine where relay nodes should be placed and how much energy they should carry.

In [10], authors compare the minimum energy consumption when the relay nodes' locations are predetermined and when they can be placed in any location. The authors provide a heuristic method to solve this problem. In [11], a similar mixed-integer nonlinear programming solution is provided to discover the optimal locations of relay nodes iteratively.

2.4 Mac Protocols

Another important issue in the study of Wireless Sensor Networks (WSNs), are the MAC protocols, which arose from the requirement to achieve an efficient consumption of energy within the network. Some application scenarios for Wireless Sensor Networks (WSNs) often involve battery-powered nodes being active for considerable lengths of time, several months to years, without external control by human operators after initial deployment. Since the batteries have a limited capacity of energy, the use of these without any type of energy strategy can cause that a node will deplete its batteries within a couple of days. This fundamental need for energy-efficient operation has drawn the attention to the radio, which is the component of a typical sensor node that consumes most energy.

Energy saving is achieved at the MAC protocol by duty-cycling the radio, that is, repeatedly switching it between active and sleep modes. This is the only way to achieve the required two orders of magnitude reduction in energy consumption for extending lifetime from days to years. This duty cycling effectively reduces the available bandwidth on the radio channel, and hence limits the amount of data that can be communicated through the sensor network.

In active mode, a node can receive and transmit packets, while in the sleep mode, it completely turns off its radio to save energy. However, forwarding a packet over multiple hops in duty-cycled MAC protocols often requires multiple operational cycles, where nodes have to wait for the next cycle to forward data at each hop.

In [7] authors investigate the inherent trade-off between energy consumption and e2e delay from a game theory perspective applied to six Wireless Sensor Network (WSN) MAC protocols; B-MAC, X-MAC, RI-MAC, SMAC, DMAC, and LMAC. In this work the two optimization objectives (energy consumption and e2e delay) are considered as game players. The cost model of each player is mapped through a generalized optimization framework onto protocol specific MAC parameters. From the optimization framework, a game is first defined by the Nash Bargaining Solution (NBS) to assure energy-consumption and e2e delay balancing. Secondly, the Kalai-Smorodinsky Bargaining Solution (KSBS) is used to find equal proportion of gain between players. The result shows the effectiveness and scalability of such framework in optimizing protocol parameters that achieve a fair energy-delay performance trade-off under the application requirements.

In [12] the author shows a study of the different MAC protocols in the literature. In his work he mentions that these protocols differ in how performance (latency, throughput) is traded off for a reduction in energy consumption. He also mentioned that the performance of each protocol depends on specific details of the application. In that work, he seeks to discover which is the best protocol for low data-rate applications where collisions are of little concern, making an analytical approach tractable in which latency and energy consumption are modeled as functions of key protocol parameters (duty cycle, slot length, number of slots, etc.).

These MAC protocols all trade off performance (latency, throughput) for a reduction in energy, but differ in complexity and flexibility to adapt to traffic fluctuations, topology changes, and varying channel conditions. That's why developers of long-running applications must be careful in selecting the MAC protocol that suits their needs best, so that they can squeeze the most out of the limited hardware resources.

Chapter 3

Models and equations

In this chapter we proceed to describe in detail the network and traffic model used in this simulation, the main features of the radio device, the X-MAC protocol and of course the system energy used to present our findings.

3.1 Network model

For a sake of simplicity, a ring topology is used, although this modeling can be easily adapted to other network topologies, e.g. random topology or grid topology.

A spanning tree is constructed Fig. 3.1, where nodes are static and maintain a unique path to the sink and use the shortest path routing with a maximum length of D hops; the depth or number of rings of the tree. We assume a network with size of N nodes, a uniform node density on the plane and a unit disk graph communication model.

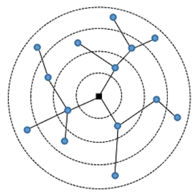


FIGURE 3.1: Spanning tree

There are $C+1$ nodes, in average, on the unit disk. Hence, all nodes are in communication range with an average number of neighbors, C, except the leaf nodes. The nodes are layered into levels according to their distance to the sink in terms of minimal hop count, $d(d = 1, ..., D)$, where $d = 0$ is reserved for the sink.

Taking the idea explained above, in Fig. 3.2, we can see an example of the topology used in this study. As we can observe a ring topology is shown with a depth of $D = 3$. In the inner ring, $D = 0$, we can find the sink node in which all network traffic is concentrated. The nodes located at the following rings has on average $C = 2$ neighbors nodes except the nodes that are in the last ring. Thus using the formula $N = (2d - 1)C$, which will be explained shortly, the total number of nodes in the network is obtained.

All values used in this study, involving the network model are summarized in Table 3.1.

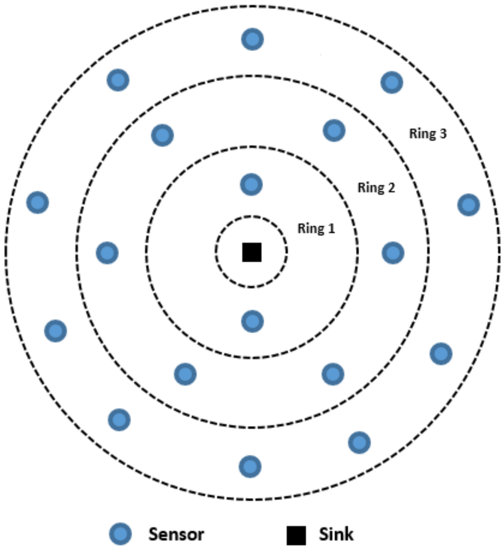


FIGURE 3.2: Sample of a ring topology, $C = 2$, $D = 3$ and $N = 18$.

Network	Parameter Description	Values
N	Network Size (number of nodes) [nodes]	200-512
D	Network Depth [levels]	5-9
C	Network Density (Connectivity) [neighbors]	4-8

TABLE 3.1: Network Parameter Values

3.2 Traffic model

For this work, we have used the traffic model used by Langendoen [12], we consider an unsaturated network topology with periodic traffic generation, which is typical of WSN applications.

In our model every source node generates traffic with frequency F_S. According to this, we will use in our modeling the terms; input F^d_{in}, output F^d_{out}, background F^d_B traffic and I_d for the input links.

The neighboring nodes, then, can be classified as the set of children (input) nodes I and the set of overheard (background) nodes, B, such that, $C = |I| + |B|$.

Using the previous topology mentioned, let us define the following parameters;

N_d is the number of nodes in ring d:

$$N_d = \begin{cases} 1, & \text{if } d = 0, \\ Cd^2 - C(d-1)^2 = (2d-1)C, & \text{otherwise.} \end{cases} \tag{3.1}$$

The average number of input links I at node at level d is:

$$|I_d| = \begin{cases} 0, & \text{if } d = D, \\ C, & \text{if } d = 0, \\ \frac{N_{d+1}}{N_d} = \frac{2d+1}{2d-1}, & \text{otherwise}, \end{cases} \quad (3.2)$$

where D denotes the maximum distance to the sink. Assuming a sampling rate of F_S, the output frequency defined as the number of packets that leaves a node is:

$$F_{out}^d = \begin{cases} F_S, & \text{if } d = D, \\ F_{in}^d + F_S = |I_d|\, F_{out}^{d+1} + F_S = F_S \frac{(D^2-d^2+2d-1)}{(2d-1)}, & \text{otherwise.} \end{cases} \quad (3.3)$$

and thus the input frequency, F_{in}^d, defined as the number of packets that enter a node is:

$$F_{in}^d = \begin{cases} F_S D^2 C, & \text{if } d = 0, \\ |I_d|\, F_{out}^{d+1} = F_S \frac{(D^2-d^2)}{(2d-1)}, & \text{otherwise.} \end{cases} \quad (3.4)$$

Finally, the aggregated background traffic frequency is:

$$F_B^d = |B_d|\, F_{out}^d = (C - |I_d|) F_{out} \quad (3.5)$$

where B^d is the average number of background nodes.

Taking the idea explained above, the network traffic does not necessarily can begin from the farthest nodes, but also the nodes located on the inner rings have the ability to generate traffic.

As we can see in Fig. 3.3, all network nodes can generate their own traffic and send it to the inner rings. Each node in the inner rings are able to generate its own traffic and also are responsible for receiving the traffic from the upper nodes and forward it to the lower nodes in order to reach the sink node.

As shown in Fig. 3.3, the closer to the sink, there will be more traffic, so that, the nodes located in the lower rings are more active causing that their wear be greater than the nodes located at the periphery of the network.

All values used in this study, involving the traffic model are summarized in Table 3.2.

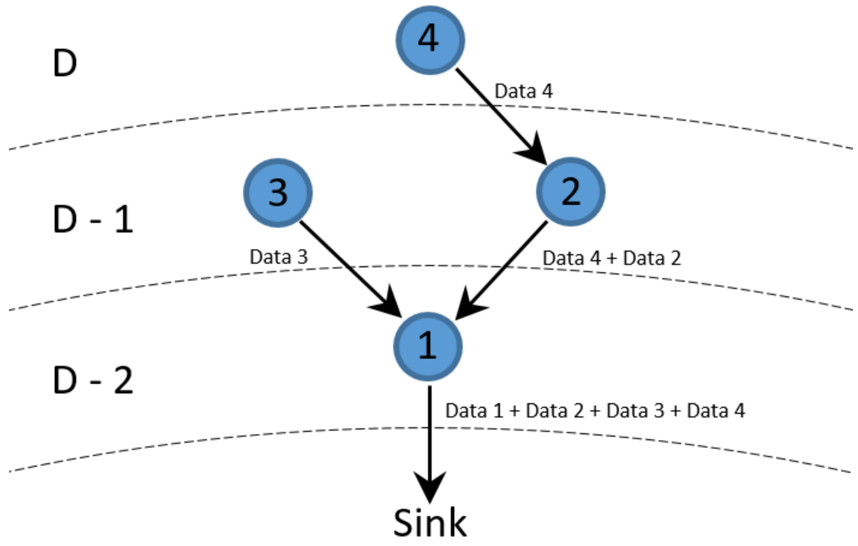


FIGURE 3.3: The traffic flows from the upper levels until reach the sink node.

Traffic	Parameter Description	Values
P	Data payload [byte]	32
F_S	Sampling rate [pkt/node/min]	$0.01 - 15$
F_I^d	Node's Input Traffic Frequency at level d	F_{out}^d
F_{out}^d	Node's Output Traffic Frequency at level d	F_S
F_B^d	Background Node's Traffic Frequency at level d	background

TABLE 3.2: Traffic Parameter Values

3.3 Radio model

Besides the network model and traffic parameters, the evaluation of a MAC model requires information about the radio hardware that will be used, in order to build the system energy and delay model.

For this part the main parameters of a radio to consider are: the time needed to power it up (i.e.,to transit from sleep into active mode), its data rate, and the time needed to do a carrier sense (including power-up), and of course the amount of energy consumed in its different states (i.e. Energy consumption in Sleep state).

In our simulation we used the CC2420 radio, Fig. 3.4, a true single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver designed for low power and low voltage wireless applications. It includes a digital direct sequence spread spectrum baseband modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps.

FIGURE 3.4: CC2420 Radio

The CC2420 is a low-cost, highly integrated solution for robust wireless communication in the 2.4 GHz unlicensed ISM band and provides extensive hardware support for packet handling, data buffering, burst transmissions, data encryption, data authentication, clear channel assessment, link quality indication and packet timing information. These features reduce the load on the host controller and allow CC2420 to interface low-cost microcontrollers.

All values used in this study, involving the radio model are summarized in Table 3.3.

CC2420 Radio	Parameter Description	Values
R	Rate $[kbyte/s]$	31.25
T_{cs}	Time $[ms]$ to turn the radio on and probe the channel	2.60
T_{up}	Time $[ms]$ to turn the radio on into RX or TX	2.40
L_{pbl}	Packet preamble length $[byte]$	4
Rx	Energy consumption in Rx state $[mA]$	19.7
Tx	Energy consumption in Tx state $[mA]$	17.4
Cs	Energy consumption in Carrier Sense state $[\mu A]$	426
$Sleep$	Energy consumption in Sleep state $[\mu A]$	20

TABLE 3.3: Radio Model with Typical Parameter Values

3.4 MAC protocol Model

The energy efficiency problem seen in WSN has produced many different specialized medium access control (MAC) protocols. The main contribution of these protocols is the duty cycling the radio that achieves the energy saving by repeatedly switching the radio between active and sleep modes. For this work we choose the duty-cycle XMAC protocol.

X-MAC is an asynchronous preamble sampling based protocol where nodes wake up periodically every T_w seconds to perform carrier sensing for, $T_{cs} + T_{al}$, (1).To send a packet, a node first contends to access the channel within the contention window T_{cw}, and it transmits a sequence of strobe preambles of duration T_{ps}, which are short packets containing the identifier of the receiver. It then listens to an acknowledgment for T_{al} (2). Strobes continue for a period sufficient to make at least one strobe overlap with a receiver wake-up (3). The receiver replies with an acknowledgment of duration T_{ack} (4) and keeps the radio on. After that, the sender transmits the

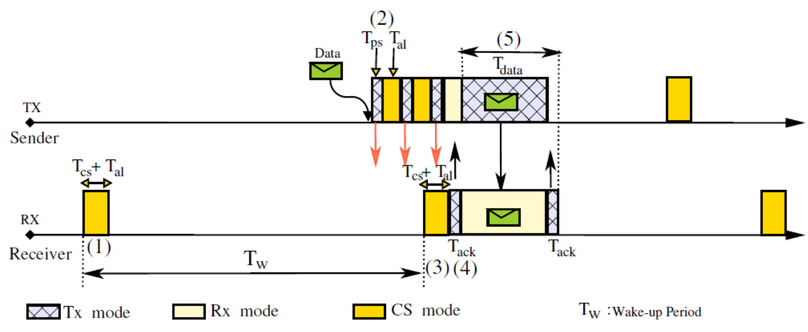


FIGURE 3.5: X-MAC's carrier sensing, transmission, and receiving modes.

data packet, T_{data}, which spans for the transmission of the header and the payload (5).

The main adjustable parameter that affects the energy and delay performance is mainly the wake-up period, T_w, and hence the vector parameter for X-MAC protocol is given by $X_{XMAC} = [T_w]$.

All values used in this study, involving the XMAC Protocol are summarized in Table 3.4.

X-MAC	Parameter Description	Values
T_w	Wake-up Period $[ms]$	$100 - 400$
L_{pbl}	Preamble length $[byte]$	4
L_{hdr}	Header length $[byte]$	$9 + L_{pbl}$
L_{ack}	ACK length $[byte]$	$9 + L_{pbl}$
L_{ps}	Preamble strobe length $[byte]$	$5 + L_{pbl}$
T_{al}	Ack listen period $[ms]$	0.95
T_{hdr}	Header transmission duration $[ms]$	$L_{hdr}/R;$
T_{ack}	ACK transmission duration $[ms]$	$L_{ack}/R;$
T_{ps}	Preamble strobe transmission duration $[mA]$	L_{ps}/R
T_{cw}	Contention window size $[ms]$	$15 * 0.62$
T_{cs}	Time $[ms]$ to turn the radio into TX and probe the channel	2.60
T_{data}	Data packet transmission duration $[ms]$	$T_{hdr} + P/R + T_{ack}$

TABLE 3.4: Values for X-MAC setting

3.5 System energy model

The energy consumption of node E^n, based on the protocol operation modes, is defined as the amount of energy consumed by the radio duty of the node in the network according to its location and the amount of traffic it handles. Hence, the energy consumption of the node is the sum of energy consumed in each operating mode, which depends on the exchanged traffic load and the XMAC intrinsic parameters.

In general, for any MAC protocol in the literature, the node's consumed energy is caused by carrier sensing E_{cs}, data transmission E_{tx}, data receiving E_{rx}, overhearing E_{ovr}, and by sending/receiving explicit synchronization, respectively denoted by E_{stx} and E_{srx}.

For example, let E^n_{cs}, E^n_{tx}, E^n_{rx} and E^n_{sleep} be the energy consumed fractions for node n in idle listening, transmitting, receiving, and sleeping modes respectively.

The normalized energy consumption (in Amperes) can be calculated by multiplying the obtained expressions in each mode by the values of the radio consumption mode defined in the Table 3.3.

The energy consumption of the node can be calculated as:

$$E^n = E^n_{cs} + E^n_{tx} + E^n_{rx} + E^n_{ovr} + E^n_{sleep} \tag{3.6}$$

where

$$E^n_{cs} = \frac{(T_{cs} + T_{al})}{T_w} \tag{3.7}$$

$$E^n_{tx} = (T_{cs} + T_{al} + T_{tx})F^n_{out} \tag{3.8}$$

$$E^n_{rx} = (\frac{3}{2}T_{ps} + T_{ack} + T_{data})F^n_{in} \tag{3.9}$$

$$E^n_{ovr} = (\frac{3}{2}\frac{T_{tx}}{T_w}T_{ps})F^n_B \tag{3.10}$$

$$E^n_{sleep} = T_w - (E^n_{cs} + E^n_{tx} + E^n_{rx} + E^n_{ovr}) \tag{3.11}$$

and

$$T_{tx} = (\frac{T_w}{T_{ps} + T_{al}})\frac{T_{ps} + T_{al}}{2} + T_{ack} + T_{data} \tag{3.12}$$

While the maximum energy consumption in the whole network is:

$$E = \sum_{n=1}^{N}(E^n_{cs} + E^n_{tx} + E^n_{rx} + E^n_{ovr} + E^n_{sleep}) \tag{3.13}$$

3.6 Delay model

The end-to-end (e2e) packet delay (latency), L^n, is defined as the expected time between the first transmission of a packet at node, $n \in N$, and its reception at the sink.

It is then a per-topology parameter, in the sense that it depends on the position of the node that generates the data. L^n denotes the sum of per-hop latencies of the shortest path, P^n, from node n to the sink, where L^n_l is the one-hop latency on each link $l \in P^n$.

The end-to-end latency of node n at level d^n is:

$$L^n_{d^n} = \sum_{i=1}^{d^n} \left(\frac{T_w}{2} + \frac{T_{cw}}{2} + T_{data}\right) \tag{3.14}$$

where

$$T_{data} = T_{hdr} + \frac{P}{R} + T_{ack} \tag{3.15}$$

3.7 The bottleneck constraint

The bottleneck is at the sink node, which has to receive all (data and sync) messages injected into the network. In order to avoid hidden terminal collisions at the sink, there should only be one message every fourth slot.

The bottleneck constraint:

$$\left|I^0\right| E^1_{tx} < \frac{1}{4} \tag{3.16}$$

where $\left|I^0\right|$ is the number of input links at level 0 (at the sink).

Chapter 4

Duty-cycle MAC protocols - Energy conservation

In this chapter we define the parameters of our baseline study before starting our research proposal in the deployment of extra relay nodes.

Basically we start defining our network topology for this study. Then based on this structure we study the behavior of the delay and energy when it is subject to certain restrictions that we have defined for this job, in order to find the best values that enable optimal latency and energy consumption. And finally using these values, the Nash Bargaining scheme is used to find the tradeoff between energy conservation and latency that gives us the best energy gain for these restrictions.

In other words, the objective of this project is to optimize a duty-cycle MAC protocol in order to minimize energy consumption and e2e delay and show that even using these tools still exist a significant percentage that can be further reduced thus ensuring additional savings and even increase the lifetime of the network. With this idea, we justify our proposal to add additional relay nodes in order to find an efficient way to balance energy.

For this part we have used the proposed equations and models used in [7].

4.1 X-Mac Protocol Analysis

The exact behavior of the MAC models depends on the settings of some protocol specific parameters. In this case the performance of XMAC strongly depends on the main adjustable parameter that affects the energy and delay performance is mainly the wake up period, Tw.

Besides of the wake up period, the optimal settings of the X-MAC protocol parameters depend on other external conditions like the traffic rate F_s, the network model and the radio characteristics.

In the analysis presented in this section we set the wake up period and the sampling rate in the interval $T_w \in [100, 40][ms]$ and $F_s \in [1, 15][pkt/node/min]$ respectively and for the network and radio, we used the parameters previously defined in Table 3.3. For these settings we compute the performance metrics of interest, for example, latency and energy efficiency.

The equations used to calculate the energy consumption are:

$$E^{XMAC} = \max_{n \in N}(\frac{\alpha_1}{T_w} + \alpha_2 T_w + \alpha_3) \tag{4.1}$$

where

$$\alpha_1 = T_{cs} + T_{al} + \frac{3}{2}T_{ps}(\frac{T_{ps} + T_{al}}{2} + T_{ack} + T_{data})F_B^{d^n} \tag{4.2}$$

$$\alpha_2 = \frac{F_{out}^{d^n}}{2} \tag{4.3}$$

$$\alpha_3 = (\frac{T_{ps} + T_{al}}{2} + T_{cs} + T_{al} + T_{ack} + T_{data})F_{out}^{d^n} + (\frac{3}{2}T_{ps} + T_{ack} + T_{data})F_{in}^{d^n} + \frac{3}{4}T_{ps}F_B^{d^n} \tag{4.4}$$

The equations used to calculate the e2e delay of the network are:

$$L^{XMAC} = \max_{n \in N}(\beta_1 T_w + \beta_2) \tag{4.5}$$

$$\beta_1 = \sum_{i=1}^{d^n} \frac{1}{2} \tag{4.6}$$

$$\beta_2 = \sum_{i=1}^{d^n} (\frac{T_{cw}}{2} + T_{data}) \tag{4.7}$$

4.1.1 Energy consumption

The energy consumption (duty cycle) of XMAC depends on the main adjustable parameter that affects the energy performance is mainly the wake up period, T_w. In XMAC the nodes are required to perform a (synchronized) carrier sense in every slot each wake-up period T_w to check for a potential message.

Setting the network topology in $d = 9$, $c = 4$, resulting in a total of 324 nodes, in Fig. 4.1 we can see that the number of packets sent every half hour F_s has a significant impact on energy consumption. Observing the energy consumption as a function of different frequencies, we can see that it clearly has two different behaviors, one behavior for small frequencies and one behavior for large frequencies.

In the case of setting a small frequency, we can see that as T_w becomes larger the energy tends to decrease. In the case of setting a large frequency, we can see how energy descends and starts to rise rapidly. For this case we can see that a large value of T_w increases the energy consumption. This is because when the protocol is forced to spend more time in sleep state, when a node wants to send a packet, it will spent more time in state x sending bicons for a longer time until the other node wakes up and receives its

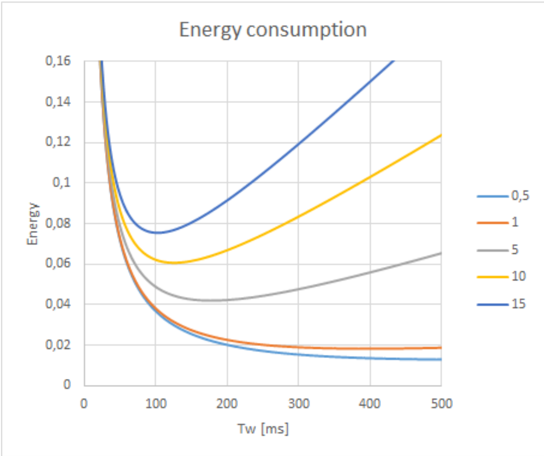
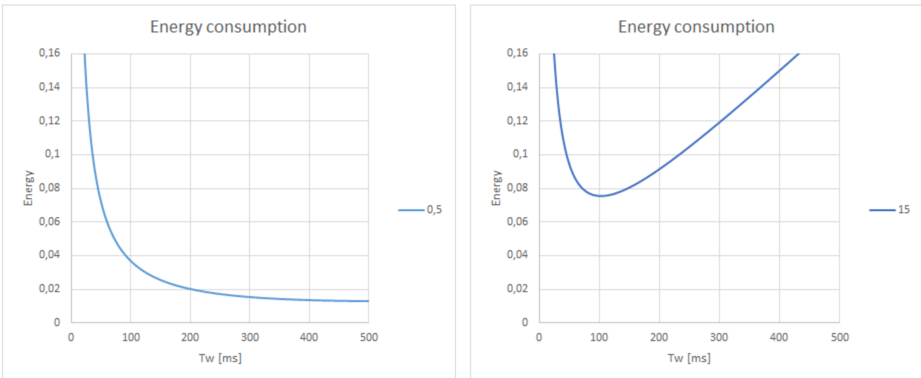


FIGURE 4.1: Energy consumption for different values of F_s.

packet and so on for the other nodes, which makes consumption increase. In other words, when we increase the frequency of packets, it results in a progressive power consumption. Taking into consideration the behaviour of T_w, we note that when the amount of traffic increases a larger wake-up period is needed.



(a) Case 1: Low frequency F_s

(b) Case 2: High frequency F_s

FIGURE 4.2: Behavior of energy consumption as a function of different frequencies of F_s.

By studying the two extreme cases seen in Fig. 4.2, setting a high traffic rate (15 packages every half hour), it is shown that energy tends to increase while in the other hand using a small traffic rate (0,5 packages every half hour) the energy consumption tends to decrease. With that analysis we can see that this kind of protocol is ideal in scenarios where a high packet traffic is not required, maintaining a small power consumption.

4.1.2 Delay

In XMAC the delay is translate as the minimum amount of time between message and message. This means that by having a small wake-up period

T_w, the protocol becomes more active, since the waiting time is reduced more packets are sending per time unit. On the other hand by defining a long wake-up period, the amount of time between each message will be higher resulting in a low activity inside the protocol.

As we can see in Equation 4.5 and Fig. 4.3, the latency of XMAC has a linear behavior, always depending on T_w. Also can be seen that the frequency has no impact on the behavior of the delay so this remains constant for different values of traffic rate F_s.

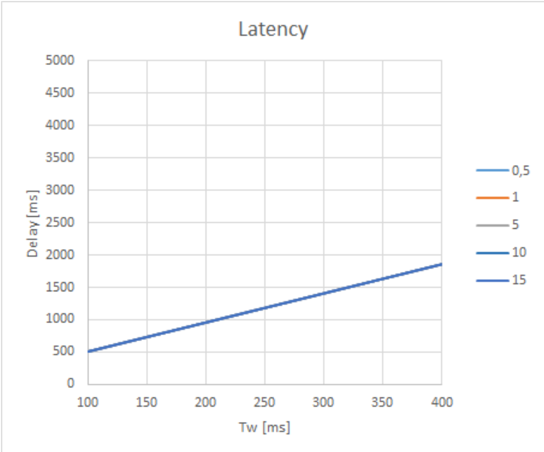


FIGURE 4.3: e2e Packet Delay for different values of F_s.

4.1.3 Latency vs Energy

Analyzing the calculated values of energy consumption and the e2e delay seen in Fig. 4.1 and Fig. 4.3 for different values of F_s, where F_s depends on the wake-up period T_w, we can see clearly a correlation between the energy consumption and the e2e delay.

In Fig. 4.4, it can be observed that when the objective is to reduce the e2e delay, it causes a rising of energy consumption while to maintain a low power consumption is achieved at the cost of high latency.

Now we know how the length of the wake-up period, T_w has impact in the behavior of the e2e latency and energy separately, and how this period creates a correlation between both of them, the next step is optimize the T_w parameter.

So the objective is to obtain the optimal value for the tuning parameter Tw that minimizes energy consumption and e2e delay in a fair manner.

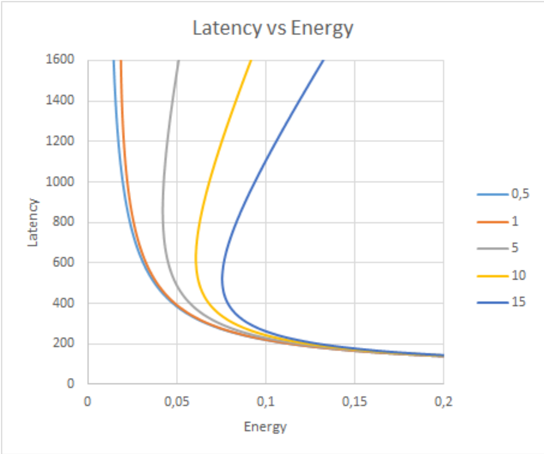


FIGURE 4.4: e2e Delay vs. Energy for different values of F_s.

4.2 X-Mac Protocol Optimization

So far we have located and identified three possible scenarios for optimizing the wake-up time T_w. The first scenario would be for applications where the delay is not a problem and is required an optimal energy consumption. The second scenario would be for applications where energy consumption is not a problem and is required a specified delay.

For the third one scenario would be where a balance is sought between energy consumption and e2e delay that is to say find the optimal value for wake-up value T_w that minimizes energy consumption and e2e delay in a fair manner.

In order to find the optimal trade-off solution for scenario one and scenario two, we define a bargaining problem in which each optimization problem represents a player, i.e., player Energy and player Latency. The Bargaining problem is a problem of understanding how several agents should cooperate when non-cooperation leads to Pareto-inefficient results. The solution of the problem is one that coincides to the solution that an arbitrator would recommend. In order to solve this problem the Nash Bargaining Solution (NBS) is used.

For the first scenario we will use the optimization problem $(P1)$, for the second the optimization problem $(P2)$ and for the last one the Nash Bargaining scheme (NBS).

4.2.1 Energy Optimization for Duty-Cycled MAC

Since we want to optimize energy consumption, we take the worst case conditions. Due to the nature of our network, we know that the most traffic rate is located in the nodes closest to the sink, more specifically the nodes located in the ring number one, $d = 1$, so we take this value as the biggest energy consumption that a node can have. That means, that related to equations in chapter 3, in the energy equations, $F_{out}^{d^n}$, $F_{in}^{d^n}$ and $F_B^{d^n}$ have to be accorded to $d^n = 1$.

Given the application requirements in terms of e2e packet delay bound L_{max}, energy optimization derives optimal MAC parameters that give the minimal network energy consumption subject to L_{max}:

$$\begin{array}{lll} (P1) & Minimize & E^{XMAC}(T_w) \\ & s.t. & L^{XMAC}(T_w) \leq L_{max} \\ & & T_w \geq T_w^{min} \\ & & \left|I^0\right| E_{tx}^1 < \frac{1}{4} \\ & Var. & T_w \end{array} \tag{4.8}$$

where L_max is the maximum latency tolerated by the application.

In Fig. 4.5, we show the results of our tests for the optimization of energy subject to delay. For this we have defined an interval $L_max \in [0.15][S]$ that we have used to solve our optimization problem (P1). As in the previous simulations the values have been set at $d = 9$, $c = 4$. Once defined our topology we set different frequencies and in each one, we tested different values of L_{max} to locate the different optimum points.

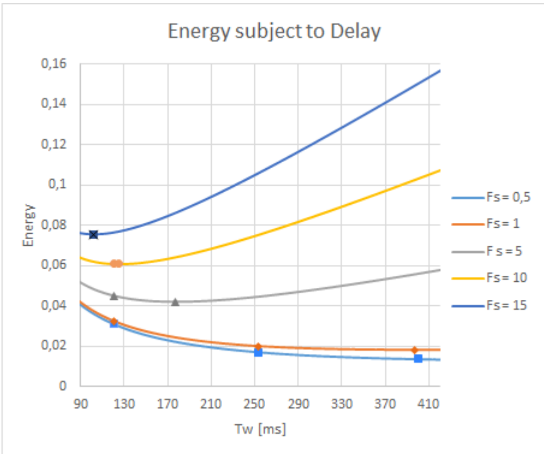
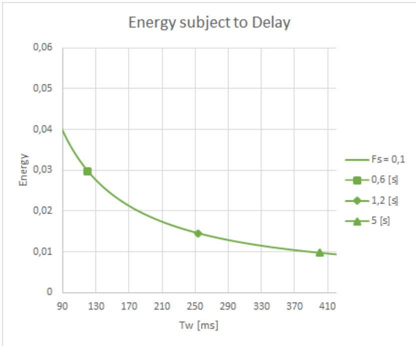
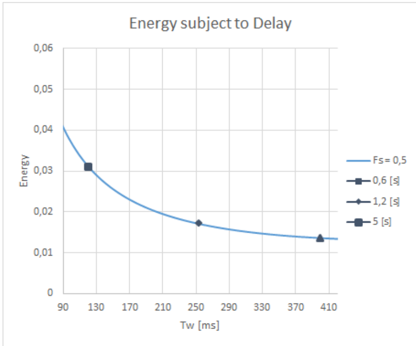


FIGURE 4.5: Energy consumption subject to several values of Latency

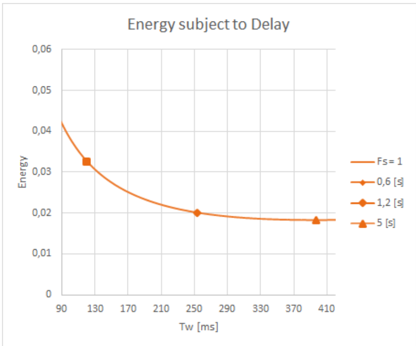
In the figure mentioned we can see different minimum points for different frequencies. As we mentioned before there are two different behaviors, one where energy tends to decrease and another where it decreases and rises sharply. In the simulations with a low traffic frequency, in the interval L_{max}, it shows that for values between 0.1 and 5 seconds it is possible to find different optimal points that satisfy our maximum latency condition. While for applications that requires a higher frequency, case 2, we observe that as traffic increases, it can be noticed how the optimum point begins to converge towards a single point. For example in Fig. 4.6 case:f, it does not matter the value of L_{max}, in the interval [0.1, 5], the result will always give the same optimum point. Which is obvious since we are facing the global minimum of our energy consumption.



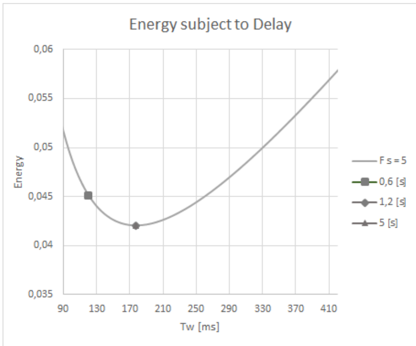
(a) $F_s = 0.1$



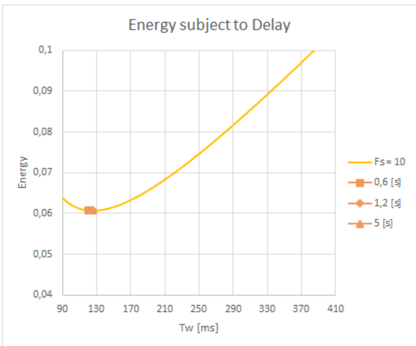
(b) $F_s = 0.5$



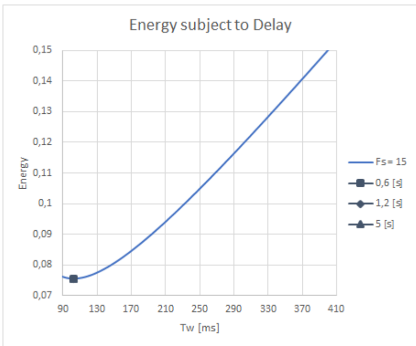
(c) $F_s = 1$



(d) $F_s = 5$



(e) $F_s = 10$



(f) $F_s = 15$

FIGURE 4.6: Behavior for Minimum energy consumption for several values of F_s subject to different values of delay, L_{max}.

4.2.2 Delay Optization for Duty-Cycled MAC

Since we want to optimize the delay, we take the worst case conditions. Due to the nature of our network, we know that the maximum delay allowed in the network is from the nodes located in the periphery of the network, $d = D$. That means, that related to equations in chapter 3, the delay equations 3.14 have to be accorded to $d^n = D$.

Given the application requirements in terms of maximum energy budget E_{budget} expressed as the maximum allowed duty cycle, we are interested in finding the optimal MAC parameters that give the minimum e2e packet delay subject to maximum energy budget:

$$\begin{array}{lll} (P2) & Minimize & L^{XMAC}(T_w) \\ & s.t. & E^{XMAC}(T_w) \leq E_{budget} \\ & & T_w \geq T_w^{min} \\ & & \left|I^0\right| E_{tx}^1 < \frac{1}{4} \\ & Var. & T_w \end{array} \tag{4.9}$$

where E_{budget} is the energy budget (maximum duty cycle) that a node consumption cannot exceed for fulfilling a lifetime target.

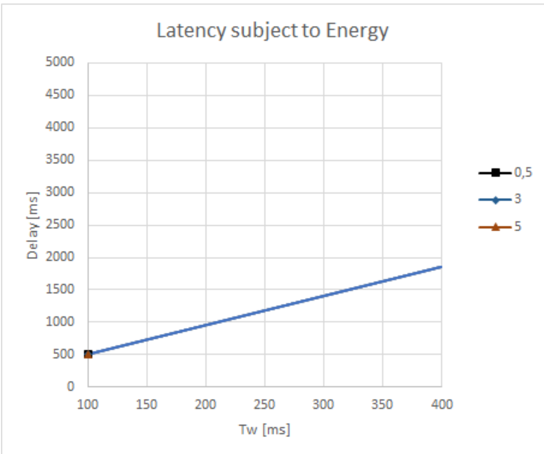


FIGURE 4.7: Latency subject to several values of Energy consumption (E_budget)

As we already mentioned before the traffic rate F_s has no positive or negative impact on the delay so always it remains constant for different values of F_s.

Even using different values of E_{budget} for solve the optimization problem (P2), the solution is always the same. By having a linear behavior, it can be seen perfectly in Fig. 4.7 which is its lowest point for all values of F_s. Also the selected values for Maximal Energy $E_{budge} \in [0.5, 5]$ not present a significant value hence you always will obtain a minimum point $508, 554[s]$ for T_w = 100 for all different values of E_{budget} and F_s.

4.2.3 The Nash Bargaining Solution (NBS) for Duty-Cycled MAC

The Nash bargaining solution, Fig. 4.8 is a simple two-player game used to model bargaining interactions. In the Nash bargaining game, two players demand a portion of some good, in this work our players are Energy and Latency and they are demanding some time (Wake-up time T_w) in order to decide how much energy will be used in sending and receiving messages (Duty cycle) and how much time the protocol have to wait between message and message. If the total amount requested by the players is less than that available, both players get their request. If their total request is greater than that available, neither player gets their request. A Nash bargaining solution is a Pareto efficient solution to a Nash bargaining game.

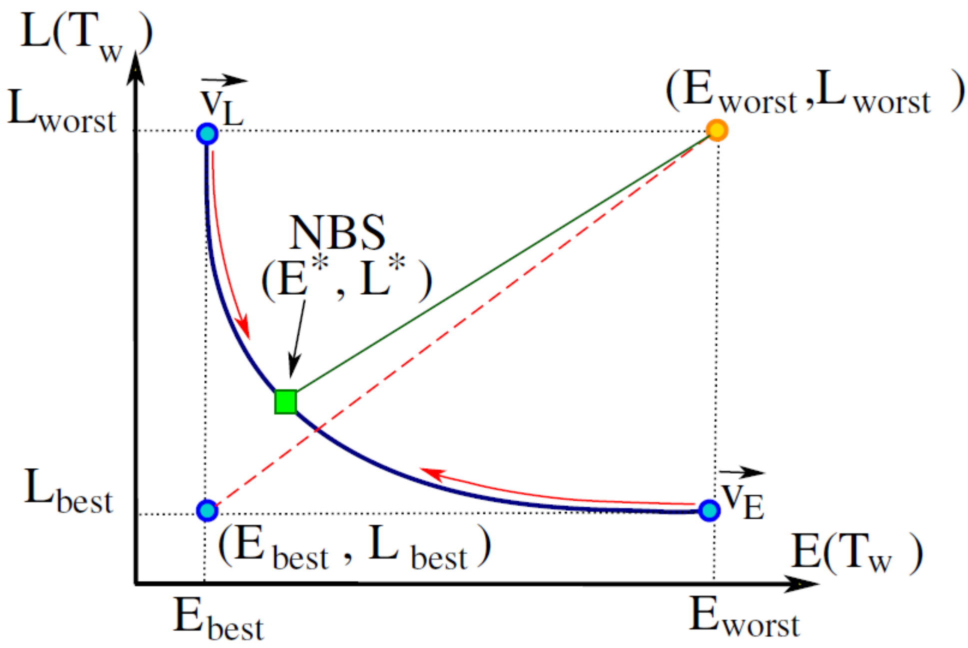


FIGURE 4.8: The Nash Bargaining Solution (NBS). The solution (E^*, L^*) of the optimization problem (NBS) where $E^* = E(X^*)$ and $L^* = L(X^*)$ will be the optimal cost for both players under the agreement.

In this game, let intervals $A_E = [E_{worst}, E_{best}]$ and $A_L = [L_{worst}, L_{best}]$ be the set of strategies that respectively player energy and player delay may take, and $s_E \in A_E$, $s_L \in A_E$ the strategies chosen by the players. The threat strategy for player delay is to play strategy, L_{best}, that makes the player energy to get, E_{worst}. On the other hand, the threat strategy for player energy is to play strategy, E_{best}, that makes the player delay to get, L_{worst}. Let $v_E = E_{worst}$, and $v_L = L_{worst}$, be the threat values of each player, where each threat value represents the utility threshold of each player to sign the agreement. If no feasible solution is found, each player gets a cost $\phi(S; v) = \infty$. Note that $E(X)$ and $L(X)$ are cost functions instead of utility functions, i.e., signs have to be reversed, and the term $(E(X), L(X)) \in S$ represents the intrinsic conditions that each MAC protocol has to fulfil. The (NBS) problem is expressed as:

$$
\begin{aligned}
(NBS) \quad & max \quad (E_{worst} - E(T_w))(L_{worst} - L(T_w)) \\
& s.t. \quad (E_{budget}, L_{max}) \geq E(T_w), L(T_w) \\
& \qquad (E_{worst}, L_{worst}) \geq E(T_w), L(T_w) \\
& \qquad E(T_w), L(T_w) \in S \\
& Var. \quad T_w
\end{aligned} \tag{4.10}
$$

where the $E(T_w), L(T_w) \in S$ means that we have to include the MAC protocol intrinsic conditions and where the point (E_{worst}, L_{worst}) is the disagreement point. The problem (NBS) is non-linear non-convex, but this kind of problems can be transformed into a standard convex optimization problem without changing its solution. The idea is to define auxiliary variables E_1 and L_1 such that $E_1 \geq E(T_w)$ and $L_1 \geq L(T_w)$, which should be satisfied by the optimal solution. Wheneverthe problem (NBS) is feasible, $E(T_w) \leq E_{worst}$, $L(T_w) \leq L_{worst}$, and application of (NBS) to the MAC protocols yields a concave problem.

$$
\begin{aligned}
(NBS^*) \quad & max \quad \log(E_{worst} - E_1) + \log(L_{worst} - L_1) \\
& s.t. \quad (E_{worst}, L_{worst}) \geq (E(T_w), L(T_w)) \\
& \qquad (E_1, L_1) \geq (E(T_w), L(T_w)) \\
& \qquad (E_1, L_1) \leq (E_{budget}, L_{max}) \\
& \qquad (E_1, L_1) \in S \\
& Var. \quad E_1, L_1, T_w
\end{aligned} \tag{4.11}
$$

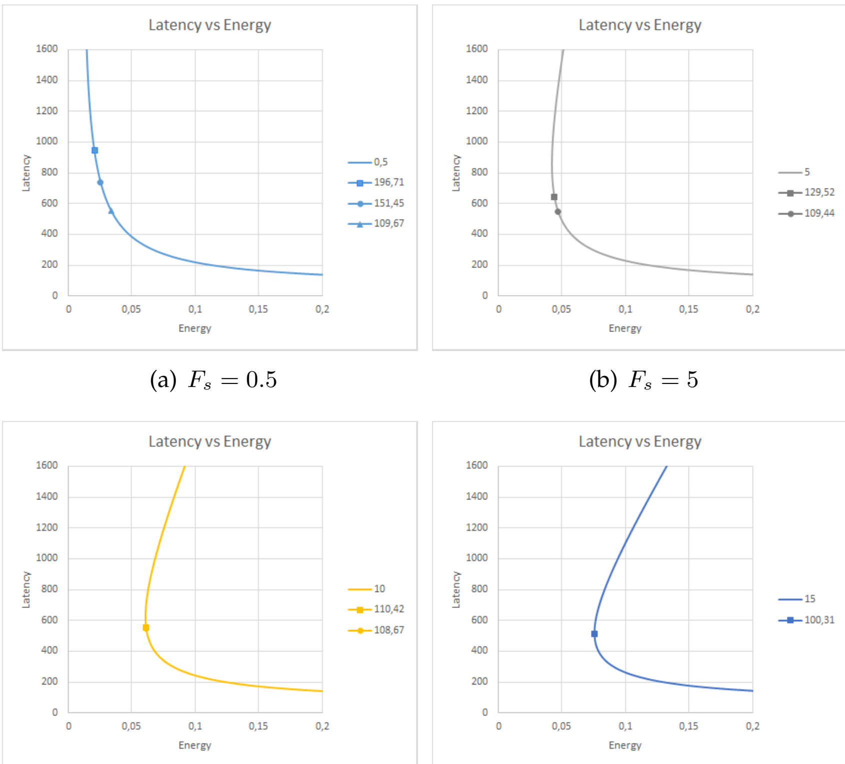
Consequently, the equivalent concave problem for XMAC is:

$$
\begin{aligned}
(NBS - XMAC^*) \quad & max \quad \log(E_{worst}^{XMAC} - E_1) + \log(L_{worst}^{XMAC} - L_1) \\
& s.t. \quad E_{worst}^{XMAC} \geq E^{XMAC}(T_w) \\
& \qquad E_1 \geq E^{XMAC}(T_w) \\
& \qquad L_{worst}^{XMAC} \geq L^{XMAC}(T_w) \\
& \qquad L_1 \geq L^{XMAC}(T_w) \\
& \qquad T_w \geq T_w^{min} \\
& \qquad \left|I^0\right| E_{tx}^1 < \tfrac{1}{4} \\
& Var. \quad E_1, L_1, T_w
\end{aligned} \tag{4.12}
$$

4.2.4 Trade-Off Energy vs Latency

As we mention before the objective of use the NBS is to obtain the optimal value T_w that minimizes energy consumption and e2e delay in a fair manner. For analyzing this trade-off, the optimization problems (P1) and (P2) were solved first in order to determine the best values that permit to achieve optimal energy and delay objectives.

The image below shows the results of calculating different equilibria points. As we have already commented, we have detected different behaviors as we have varied the frequency. Fig. 4.9(a) shows the best equilibria points when we have a low frequency F_s. As we can see, when we have a low frequency it is more likely that different combinations of latency and energy constraints (e.g. setting a delay value and varying it with different energy values or vice versa) produce different equilibrium points. While in the presence of high frequencies the combination of these restrictions produce a series of very close points between them that show a tendency to converge in a single point Fig. 4.9(d).



(a) $F_s = 0.5$ (b) $F_s = 5$

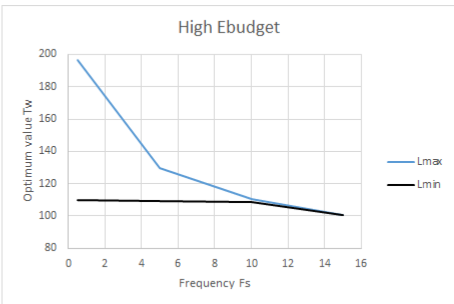
(c) $F_s = 10$ (d) $F_s = 15$

FIGURE 4.9: Different equilibria points subject to several values of $L_{max} \in [0.1, 5]$ and $E_{budget} \in [0.1, 5]$

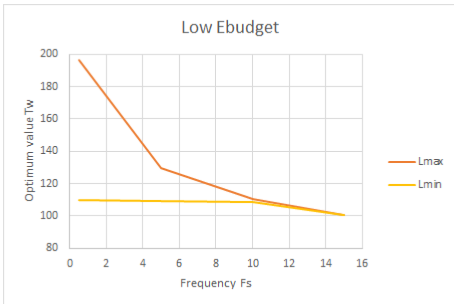
Analyzing these results we have noticed that the frequency affects the efficiency of the duty cycle. As shown in Fig. 4.2, where both a very short and a very long sampling period will result in a high duty cycle (i.e., low efficiency), but their causes differ. While a short polling period will increase the energy consumption for idle listening, a long one will increase the energy consumption for transceiving the wakeup preamble. This has led us to study, how these constraints behave when frequency increases, at the time of calculating our optimal T_w.

Fig. 4.10 shows the behavior of T_w with respect to different frequencies using different combinations of constraints. In the mentioned figure we have summarized four different scenarios. In Fig. 4.10(a) we have a high value of E_{butget} (i.e. 5 $[mA]$) where we have varied the delay L_{max} (from 5 to 0.6 seconds). In Fig. 4.10(b) we have a low value of E_{budget} (i.e. 0.1 $[mA]$) and we have varied the latency L_{max}. In Fig. 4.10(c) we have set a high delay L_{max} (i.e. 5 seconds) value and we have varied the energy E_{budget}. And finally in Fig. 4.10(d) we have set a small delay value and we have varied the energy.

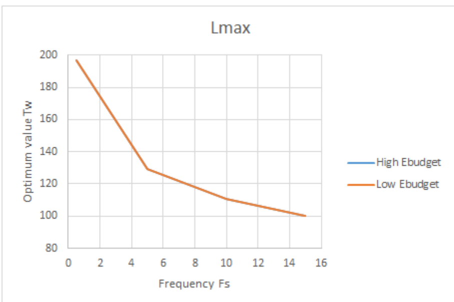
For example, Fig. 4.10(a) a shows the behavior of our optimal T_w when we set a high E_{budget} (for example 5 $[mA]$) and use high and low delay values, L_{max} and L_{min} respectively. In this case it is seen that using a very large delay, the value of T_w tends to fall very fast to compensate for a longer wait time, whereas when we use a small delay the value of T_w tends to be more stable. According to our results we have noticed that when setting an energy value no matter if it is high or low, the delay has a great impact on T_w Fig. 4.10(a) and Fig. 4.10(b). While fixing a latency value and subjecting it to different energy values, it does not affect the behavior of tw at all, Fig. 4.10(c) and Fig. 4.10(d). In other words, between delay and energy, delay is the most influential factor in the energy consumption of a wireless sensor networks.



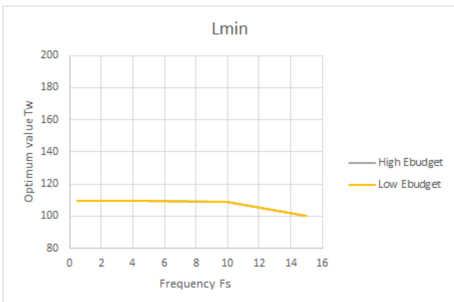
(a) High E_{budget} with different latencies



(b) Low E_{budget} with different latencies



(c) High latency with different E_{budget}



(d) Low latency with different E_{budget}

FIGURE 4.10: Trend of optimum T_w for several values of frequency F_s

Chapter 5

Adding extra relay nodes

In this chapter, we propose a modification to the original model proposed by Langendoen [12], which allows the addition of extra nodes of relay class, in other words nodes that do not generate any type of data and only direct the existing traffic towards the sink, with the objective of reducing the energy consumption in the internal rings distributing the traffic with the help of these new nodes.

5.1 Why Add extra relay nodes?

In order to achieve equal power consumption at different levels of our network, we have decided to add extra relay nodes to reduce and balance the traffic load that normal nodes have to carry. As mentioned above, each level within the network faces a different amount of traffic, which becomes more intense as we approach the interior levels. This behavior causes that the external nodes, with less traffic to handle, stay more time at rest while the nodes in the inner rings face a great amount of traffic which forces them to be more active, generating a more accelerated exhaustion, reason why nodes located in the inner rings exhaust its battery faster causing the lifetime of the network to come to an end.

While the nodes located in the inner rings have died, the nodes in the outer rings still retain much of their energy, which tells us that the network has not yet reached its full potential.

In order to maintain a better balance we have added an Nr number of relay nodes to a common implementation (original model, [12]). Knowing that the greatest wear is generated in the internal nodes, our logic tells us that adding a greater number of relay nodes in the inner rings would reduce their wear therefore we could extend the lifetime of the network.

The how and where the new relay nodes are added is defined by a series of distributions that we have chosen for our work. The key to choosing our deployment strategy has been the natural form of linear, quadratic, and exponential functions. For example, following our analysis of attacking the problem of energy distribution in the inner rings by adding extra relay nodes, the exponential distribution fits our problem, since the shape of this distribution, suggests us to add a large number of relay nodes in the inner rings and as it continues to add fewer nodes in the outer rings. Similarly following a linear distribution it is proposed to add a number Nr relays in the inner rings and gradually decrease the quantity until reaching the last ring. We also study the wear of all nodes when we add the same number of relays per ring (uniform distribution).

All these simulations have been done with the objective of finding the best distribution that best fits our problem, achieving a better energy distribution.

5.2 New traffic model

For deriving the new traffic model, we extend the one proposed by Langendoen [12], for a homogeneous sampling rate sensor network to a model for a multi-class sampling rate sensor network in which we have two classes of nodes, nodes of normal class and nodes of relay class, where each class has its own sampling rate. For each node of normal class let F_s be the rate at which it samples the environment, and F_r be the sampling rate or each node of relay class. The purpose of the modification of the traffic model is to add extra relay nodes that do not generate traffic, so for the study of this work we set $Fr = 0$.

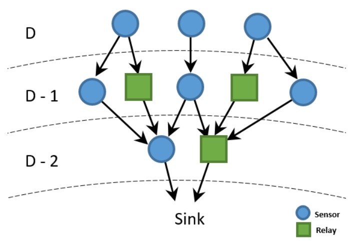


FIGURE 5.1: New traffic model

Just like the original model seen in chapter 2, we have:

$$TotalNodes = Nn + Nr \tag{5.1}$$

Where Nn represents the total number of nodes of normal class.

$$Nn = C * D^2 \tag{5.2}$$

and Nr represents the total number of nodes of relay class that will be added to the network.

$$Nr = C * D^2 * \alpha_R \tag{5.3}$$

where α_R is the percentage of extra relay nodes added in the network.

The nodes are grouped into rings according to their distance to the sink. The first ring contains C nodes, from which we can derive the node density in each ring.

The average number of nodes of normal class N_d in ring d is,

$$N_d = (2d - 1)C \tag{5.4}$$

and the average number of nodes of relay class in ring d is R_d. How R_d is calculated, is shown in the following section.

5.3 Deployment distributions

As we discussed a moment ago the deployment of the number of relays R_d in the ring d depends on the distribution that is being used.

In this section different deployment strategies are proposed, maintaining the common goal of adding a greater number of relays nodes in the inner rings, where they are necessary because of the high amount of traffic and fewer relay nodes in the external rings where they are not so necessary. In other words the deployment strategy will follow a tendency to progressively add a number Nr of relay nodes from the periphery of the network to the inner rings.

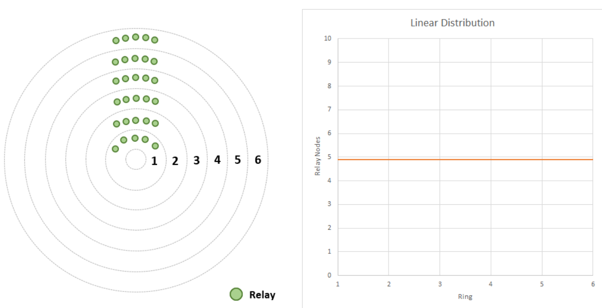
To study and compare the impact of adding this type of nodes we propose four different deployment strategies, based on their natural increase; uniform, linear, quadratic and exponential.

5.3.1 Uniform distribution

Since the objective is to study the effect of different strategies, we have started using the simplest and most common one by placing a Nr number of relay nodes in an equal proportion on all the rings in our network except in the last one.

First, we define the number of relay nodes that will be added to each ring, in this case being a uniform distribution, we add the same number of relay nodes to each ring except the last one. The purpose of these relay nodes is to direct and reduce the traffic without generating any type of data, so having this type of nodes in the last ring is useless Fig. 5.2, so we distribute the number of relay nodes that will be aggregated between $D-1$ rings.

$$R_d = \frac{Nr}{D-1} \tag{5.5}$$

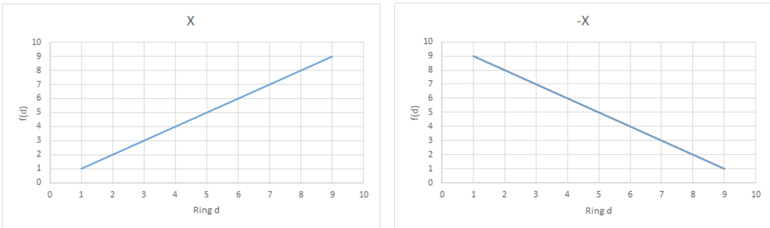


(a) Uniform Deployment (b) Uniform Distribution

FIGURE 5.2: Uniform deployment strategy

5.3.2 Linear distribution

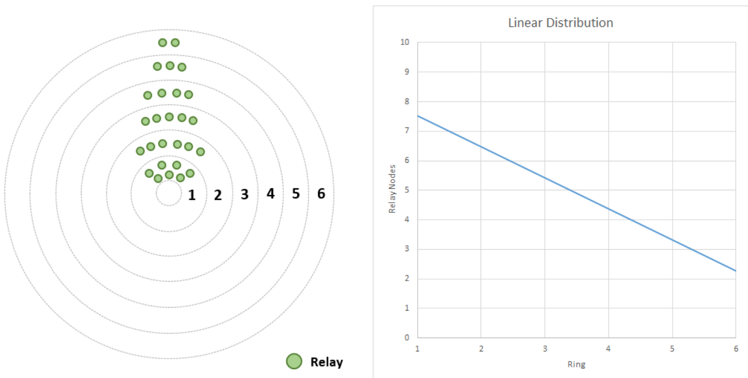
For this strategy we have chosen two behaviors, when it has a positive slope and when its slope is negative, Fig. 5.3. We use the positive behavior to add the relay nodes starting from the ring d = 1 increasing its population linearly until reaching the periphery, fewer nodes in the center, more nodes in the periphery. On the other hand we use negative behavior, starting from the periphery and continue to add relays in a linear way as we approach the center, more nodes in the center, fewer nodes in the periphery.



(a) Fewer in the center, more in the periphery (b) More in the center, fewer in the periphery

FIGURE 5.3: Linear deployment strategy

The original idea is to add a large number of relay nodes in the rings where there is more data traffic and where the population of nodes is small which causes its saturation and an early death. But we also want to know what happens when we map more nodes to the outer rings and less to the inside of the network. That is why, using this strategy, more nodes in the center fewer nodes in the periphery or fewer nodes in the center more nodes in the periphery, will help us locate where these new nodes really are needed.

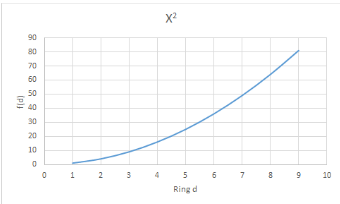


(a) Linear Deployment (b) Linear Distribution

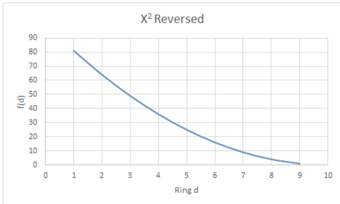
FIGURE 5.4: Example of a linear deployment following the strategy, more nodes in the center fewer nodes in the periphery.

5.3.3 Quadratic distribution

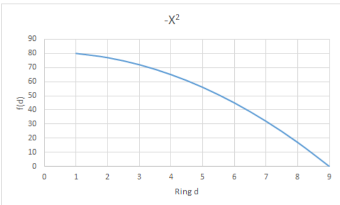
In the case of this strategy, following the same previous analysis of placing a different number of relays in the center and in the periphery, we have chosen four behaviors derived from the same function. Fig.5.5.a, shows the normal behavior of the quadratic function, Fig.5.5.b, shows the same values of the function X^2 but in the opposite direction. Fig.5.5.c, corresponds to the behavior when the function when negative, $-X^2$, but applying a small modification we change the values to positive while keeping its peculiar decreasing form. And finally Fig.5.5.d shows the aforementioned values in the opposite direction.



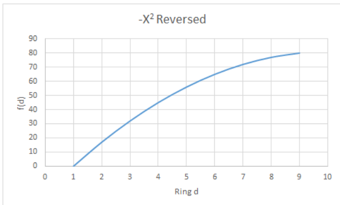
(a) Fewer in center, more in the periphery



(b) More in the center, fewer in the periphery



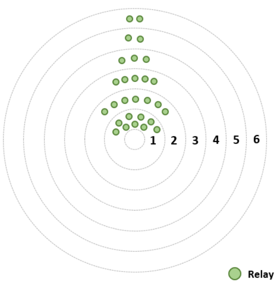
(c) More in the center, fewer in the periphery



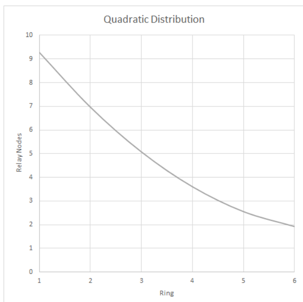
(d) Fewer in center, more in the periphery

FIGURE 5.5: Quadratic deployment strategy

Following the same strategy, more nodes in the center fewer nodes in the periphery or fewer nodes in the center more nodes in the periphery, we have obtained two increase behaviors and two decrement behaviors with a small variation in the internal rings, as the case is chosen.



(a) Quadratic Deployment



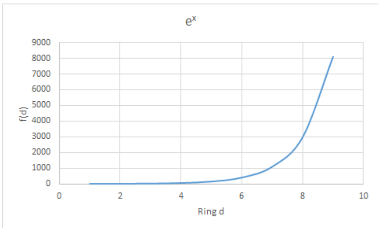
(b) Quadratic Distribution

FIGURE 5.6: Example of a quadratic deployment following the strategy, more nodes in the center fewer nodes in the periphery.

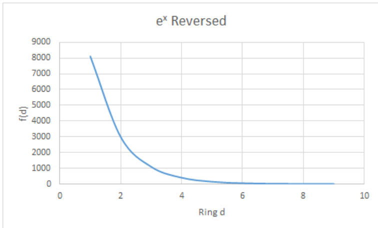
5.3.4 Exponential distribution

Finally, following the strategy of testing with different quantities of relay nodes in different parts of the network, this time we used a more aggressive distribution. In this case we have chosen to use the exponential distribution e^X since it follows a very fast increase, which makes it perfect to test our hypothesis.

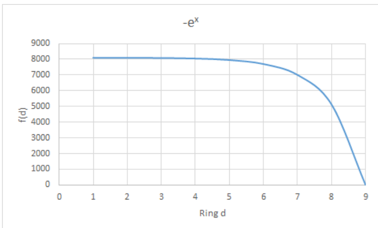
Figure 5.7.a shows the normal behavior of the exponential function. Fig. 5.7.b shows the same values of the e^X function but in the opposite direction. Fig. 5.7.c, corresponds to the behavior when the function is negative, $-e^X$, but applying a small modification we change the values to positive conserving the form where we have a high number of relay nodes in the inner rings, while in the external we find very few. And finally Fig. 5.7.d, shows the behavior of the exponential function when it is negative but in reverse.



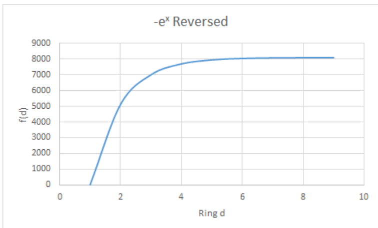
(a) Fewer in center, more in the periphery



(b) More in the center, fewer in the periphery

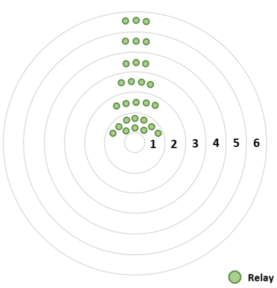


(c) More in the center, fewer in the periphery

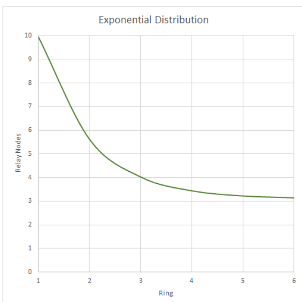


(d) Fewer in center, more in the periphery

FIGURE 5.7: Exponential deployment strategy



(a) Exponential Deployment



(b) Exponential Distribution

FIGURE 5.8: Example of a exponential deployment following the strategy, more nodes in the center fewer nodes in the periphery.

5.3.5 Formulas

First, we define our base function, in this case we have chosen the value of the rings as our input parameter.

$$f(d) = \begin{cases} d = d, & \text{if } LinearDistribution, \\ d = d^2, & \text{if } QuadraticDistribution, \\ d = e^d, & \text{if } ExponentialDistribution, \end{cases} \tag{5.6}$$

Since the purpose of relay nodes is to direct the traffic and not to generate any type of data, to have this type of nodes in the last ring is useless, so we distribute the quantity corresponding to the last ring $f(D)$ among the remaining rings in equal proportion.

$$dist = \frac{f(D)}{D-1} \tag{5.7}$$

Then, we add the value $dist$ to our base function.

$$baseFunction(d) = f(d) + dist \tag{5.8}$$

$$sumFunction = \sum_{d=1}^{D-1} baseFunction(d) \tag{5.9}$$

Where the $baseFunction$ depends on whether it is liner, quadratic or exponential.

Now we have the linear, quadratic or exponential value, $baseFunction(d)$ for each ring except for the last ring that does not contain relay nodes, so we set $baseFunction(D) = 0$, and calculate the percentage of relay nodes that will be allocated following a distribution, 5.6.

$$Distribution(d) = \frac{baseFunction(d)}{sumFunction} \tag{5.10}$$

Finally we calculate the number of relay nodes that will be added to each ring.

$$R_d = Distritution(d) * Nr \tag{5.11}$$

Having the information of how many nodes of relay class will be added per ring R_d, we calculate the new percentage of nodes of normal class and relay class per ring.

$$relayPerRing_d = \frac{R_d}{nodes_d} \tag{5.12}$$

$$normalPerRing_d = \frac{N_d}{nodes_d} \tag{5.13}$$

where $nodes_d$ is the total number of nodes of both classes in the rind d.

$$nodes_d = N_d + R_d \tag{5.14}$$

By modifying the number of nodes per ring when we adding the extra relay nodes we must calculate the new average number of input links of both classes at level d using the formula:

$$|IN_d| = \begin{cases} 0, & \text{if } d = D, \\ C, & \text{if } d = 0, \\ \frac{nodes_{d+1}}{nodes_d} * normalPerRing_d, & \text{otherwise,} \end{cases} \tag{5.15}$$

$$|IR_d| = \begin{cases} 0, & \text{if } d = D, \\ C, & \text{if } d = 0, \\ \frac{nodes_{d+1}}{nodes_d} * relayPerRing_d, & \text{otherwise,} \end{cases} \tag{5.16}$$

Assuming a sampling rate of F_S for normal nodes and $F_R = 0$ for relay nodes, the output frequency defined as the number of packets that leaves a node is:

$$F^d_{outNormal} = \begin{cases} F_S, & \text{if } d = D, \\ F_S + F^d_{inNormal} + F^d_{inRelay}, & \text{otherwise.} \end{cases} \tag{5.17}$$

$$F^d_{outRelay} = \begin{cases} 0, & \text{if } d = D, \\ F^d_{inNormal} + F^d_{inRelay}, & \text{otherwise.} \end{cases} \tag{5.18}$$

and thus the input frequency, $F^d_{inNormal}$ and $F^d_{inRelay}$, defined as the number of packets that enter a node is:

$$F^d_{inNormal,inRelay} = \begin{cases} 0, & \text{if } d = D, \\ |IN_d|\, F^{d+1}_{outNormal} + |IR_d|\, F^{d+1}_{outRelay}, & \text{otherwise.} \end{cases} \tag{5.19}$$

Finally, the aggregated background traffic frequency is:

$$F^d_{BNormal,BRelay} = (C - |IN_d|)F^d_{outNormal} + (C - |IR_d|)F^d_{outRelay} \tag{5.20}$$

where B^d is the average number of background nodes.

5.4 Implementation

Starting from a previously established implementation, we proceed to add relay nodes in an attempt to obtain a better energy distribution.

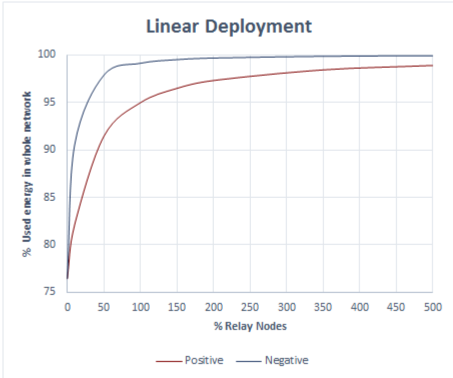
For that we have followed the following procedure:

1. Define the total percentage of relay nodes, that will be added to the network.
2. According to the chosen distribution, calculate the number of relay nodes Rd in ring d.
3. Calculate the total number of nodes of both classes in the ring d.
4. Calculate the percentage of normal nodes and percentage of relay nodes in ring d.
5. Calculate the new average number of input links of normal class IN_d and relay class IR_d.
6. Calculate the output frequency of normal class $F^d_{outNormal}$ and relay class $F^d_{outRealy}$.
7. Calculate the input frequency of normal class $F^d_{inNormal}$ and relay class $F^d_{inRelay}$.
8. Calculate the aggregated background traffic frequency $F^d_{BNormal}$ and F^d_{BRelay}.

5.5 Deployment strategies results

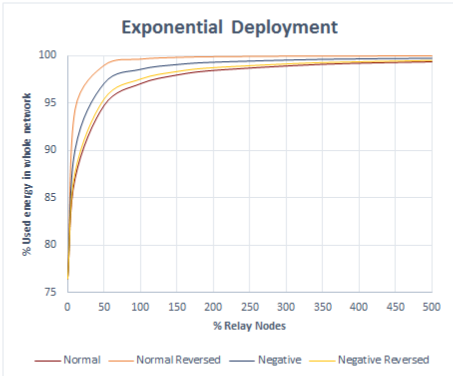
Following the analysis described in section 5.3 we tested different distributions, in order to select the best strategy that fits better to the solution of our problem.

(a) Uniform deployment



(b) Linear deployment

(c) Quadratic deployment



(d) Exponential deployment

FIGURE 5.9: Comparison of the different deployment strategies used

Figure 5.9 shows the results of different strategies put to test. The Y-axis represents the amount of energy used by the entire network at the end of its life. The X-axis defines the percentage of relay nodes that have been added in different simulations. This image shows the percentage of energy used by the network as relay type nodes have been added. As we can see, the curve starts at 76% which is the percentage of energy used by the original model. This metric helps us measure the potential of the network, for example if all the nodes exhaust their battery at the same time, at the end of the useful life of the network we will say that the network has used 100% of the available energy. In the case of the original model we know that there is no energy balance between the nodes of the network resulting in a use of 76% of the available energy, wasting the remaining 24%. When we adding nodes of relay class to the original model, we can see how this percentage increases, the closer it gets to 100%, we will ensure a better network performance, which translates into a better energy distribution in all the rings and at the same time we are extending the lifetime of the network.

Figure 5.9.a, shows the results of placing the same relay node proportion in the different rings of the network. Figure 5.9.b, shows the results of testing two linear distributions, one with positive slope and one with negative slope, with the idea of testing two different strategies, fewer relay nodes in the center and more relay nodes in the periphery, positive slope, and more relay nodes in the center and fewer relay nodes in the periphery, negative slope. Taking as a point of reference when we add 50% of relay nodes, we have that the strategy using a positive slope, we obtain a consumption of 91% of the total available energy while using a negative slope we get 97%, which is better. As we mentioned above the larger the percentage, we are ensuring a better energy distribution in all rings of the network. We realize that our assumption of adding more relay nodes in the rings near to the sink and less in the outer rings is the best strategy. The blue line is the best linear deployment and shows the results of the energy consumption using a linear distribution with negative slope. Figure 5.9.c shows the result of testing 4 strategies derived from a quadratic distribution. Two strategies following an increment, starting in the center and ending at the periphery of the network, fewer relay nodes in the center, more relay nodes in the periphery and two strategies following a decrement, starting in the center and ending at the periphery of the network, more relay nodes in the center, fewer relay nodes in the periphery. Again we find that by placing more nodes in the inner rings we achieve a better balanced consumption instead of placing more relays in the external rings. Finally in figure 5.9.d, it shows the result of comparing other 4 strategies derived from exponential distribution. Following the same analysis, once again, we test our two strategies. Again we conclude that the best strategy is to use one strategy following an increment, starting in the last ring and ending at the center of the network in other words, allocate more relay nodes in the center and fewer relay nodes in the periphery. With this result we confirm that the strategy more relay nodes in the center, less relay nodes in the periphery, fits more to the solution of our problem. In other words, adding more relay nodes in the inner rings and a smaller amount in the external rings results in a more balanced consumption, which makes the network consumes a greater percentage of the energy available before reaching its useful life.

As we can see as we deploy a larger number of relay nodes, we achieve greater use of all available energy. From deploying a 50% relay nodes, we managed to use 99% of the energy available.

Once, having selected the best strategy of its type, we compare our four types of strategies, uniform, linear, quadratic and exponential, and select the best one.

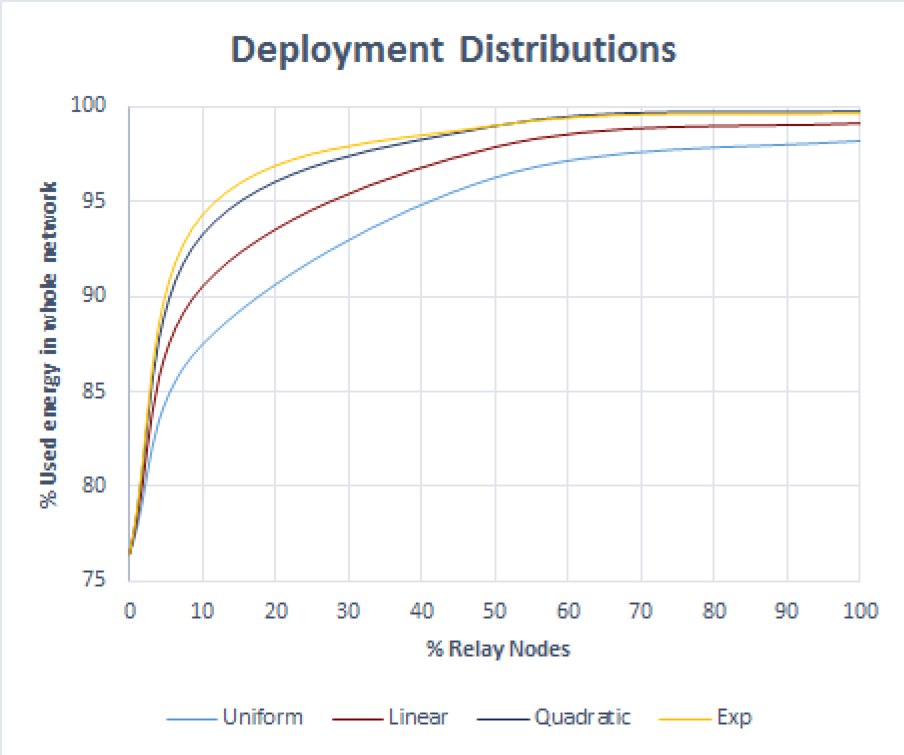


FIGURE 5.10: Results of the different deployment strategies used

Just as we expected, the best strategy turns out to be the exponential distribution, due to its nature of beginning with a soft increment and towards the end to grow of abrupt form, which makes it perfect for our study. As can be seen in figure 5.10, the use of an exponential deployment shows the best results, followed by the quadratic deployment, below in the third place we have the linear deployment and finally in the last place we have the uniform deployment. Now using this information as the basis for our final test, finally we analyze the impact of adding a number of extra relay nodes in a normal deployment, with the objective of reduce and distribute the energy in a more efficient way.

Chapter 6

Simulations and Results

In this chapter we evaluate the performance of the original model described in chapter 3 against the modification proposed in chapter 5.

6.1 Simulation parameters and metrics

For the study and simulation, both models were coded using Matlab. Remember that in our model, each node runs on batteries so the initial energy of each node is 2100 mAh, which corresponds to a common battery. We have set our sampling rate $Fs \in [1, 15] pks/half_hour$. In particular, parameters based on the network topology are given as follows: the network depth (rings) is $D \in [5, 9]$, the density of the network (connectivity) is $C \in [4, 8]$, and the number of nodes inside the network is $N \in [200, 512]$.

6.1.1 Metrics

The performance metrics used in this work are:

- The energy consumption of one node in the ring d, which is the energy spent by a node during its different states (e.g. carrier sense, sleep, Tx, Rx) in one cycle.

$$energyPerCycle^d = E^d = E^d_{cs} + E^d_{tx} + E^d_{rx} + E^d_{ovr} + E^d_{sleep} \quad (6.1)$$

- The remaining energy of one node in the ring d, which is the energy remained when the first node die, in other words when the network lifetime ends.

$$remainingEnergy^d = batery - usedEnergy^d \quad (6.2)$$

  where the used energy of one node in the rind d is the amount of energy remaining when any node in ring $d = 1$ has died. It is calculated using the number of cycles that takes for a node in the ring $d = 1$ to die.

$$usedEnergy^d = energyPerCycle^d * cycles^1 \quad (6.3)$$

$$cycles^d = batery/energyPerCycle^d \quad (6.4)$$

- The total amount of energy remaining in the whole network.

$$networkRemainingEnergy = \sum_{d=1}^{D} remainingEnergy^d * N^d \quad (6.5)$$

These three metrics are used to compare the performance of the original model against the proposed in this work using different deployment strategies.

6.2 Original Model

First of all we analyze the original model proposed by Langendoen, to understand the behavior of energy at all levels in the network. The procedure of the experiments is as follows. First chose the topology of our network and calculate the node densities of the rings using the equations seen in chapter 3. Then, using our chosen protocol for this work and the radio that will be integrated in all our nodes, we calculate the optimal value taking into account two restrictions; the interval of transmission between message and message, delay, and a budget of energy. Then we calculate the energy consumption of the nodes per ring, using the formulas in section 3.5.

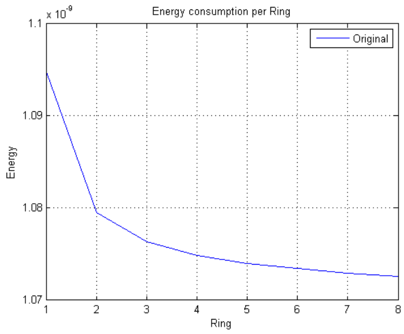
To test the original model, we deploy 324 nodes in a circular area with a density C = 4 and there are 9 levels in total. It should be mentioned that the energy consumption of all nodes in one ring is the same, so we study the consumption of one node per ring.

6.2.1 Energy consmption

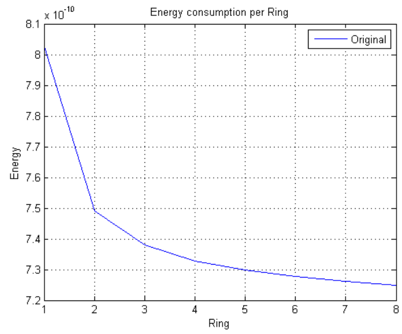
The Fig. 6.1 shows the energy consumption of one node in the ring d, using different sampling rates, F_s. We can see that no matter how often we are sending data, large or small sampling rate, the energy consumption always follows the same pattern, the energy consumption is higher as we approach the inner rings. As we had been commenting, this type of behavior is just what was expected. An unbalanced energy consumption, being lower in the periphery of the network, $d = D$ and too big in the ring closest to the sink, $d = 1$.

Recall that in this type of networks, the number of nodes increases from the inner rings to the last ring. This places a larger portion of nodes in the outer rings whereas in the inner rings, more commonly in rings 1 and 2, we find a smaller proportion of nodes. Having a large number of nodes on the periphery causes a large number of data to be generated and as these data cross the internal levels as they go into the network, this traffic increases, that is why in the internal rings, where there are a few nodes, receiving all the incoming traffic generated by the entire network makes them continuously running, exhausting their battery sooner.

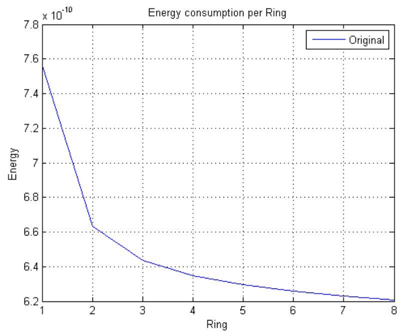
As shown in the figure, in the rings 1 and 2, especially ring 1, the energy consumption is disproportionately large so it is expected that the life time of the nodes located in this ring will be shorter.



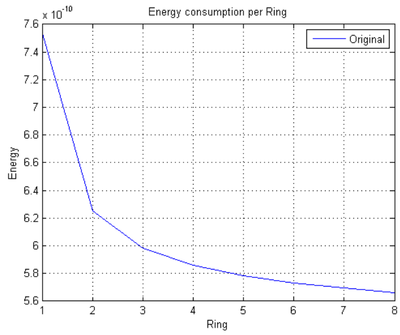
(a) $F_s = 1$



(b) $F_s = 5$



(c) $F_s = 10$



(d) $F_s = 15$

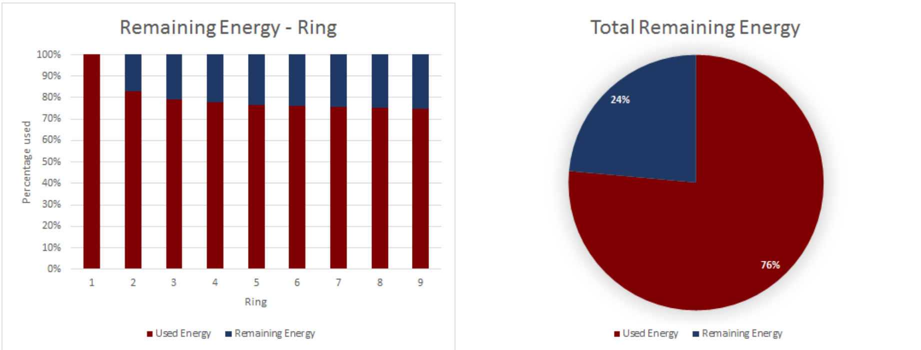
FIGURE 6.1: Energy consumption per ring for different values of F_s

6.2.2 Remaining Energy

It's important to mention, that a node in the network is considered dead when it is unable to forward any data or send its own data. The network life time is defined as the duration from the very beginning of the network operation until the first node dies.

Using the values mentioned in section 6,1, we start the operation of the network by setting the same amount of energy in all the nodes and stop the operation when the first node in exhausting its battery appears. Just at that moment using the formulas seen in section 6.1.1 we perform an analysis of all the nodes focusing on the amount of energy left in their batteries.

The Fig. 6.4 shows the remaining energy of each node when the network lifetime ends. As we can see the nodes located in the outer rings have on average at least 23% of their energy unused when the network lifetime ends. In the other hand the nodes located in the inner rings, more especially the nodes located in the ring $d = 1$, have exhausted their batteries. This brief analysis tells us that all the nodes in the network do not exhaust their batteries at the same time.In figure b, a summary of all the energy within the network is shown. We can see that the network has only spent 76% leaving almost a quarter of the energy available unused. This confirms our hypothesis that the network can still achieve greater potential by finding a strategy to balance energy consumption across all nodes, extending its useful life considerably.



(a) Remaining energy per rind (b) Remaining of the whole network

FIGURE 6.2: Remaining Energy when the network lifetime ends.

As we have already commented, in this type of networks it is very common that the nodes located in the first ring die faster since they must support an almost constant activity, of forwarding traffic from the upper levels to the sink, so it's no surprise that at the end of the useful life of the network many nodes still conserve energy.

6.3 Extended Model

Having confirmed that there is no balanced energy consumption between the nodes of the network, which causes that it has a premature end because of, a disproportionate consumption of energy of the nodes in the ring d=1, we have proposed adding an extra number of relay nodes in the most energy-intensive rings. The original strategy was to put a huge amount of these nodes in the inner rings near the sink to help them in traffic distribution and prevent them from consuming their battery in a hurry, while in the rings near the periphery place the few possible. Since we checked in section 5.4, that our initial supposition was correct, the best deployment strategy for this work is to add a number Nr of relay nodes that follow an exponential distribution. In other words to place a big number of relay nodes in the center of the network and begin to decrease their number in exponential progression until reaching the periphery obtaining more nodes in the center and fewer nodes in the periphery. We have fixed the use of this strategy in all our simulations.

In this way, following our process of experimentation; first, as with the original model, we use the same topology, radius, delay, and energy values. Second, by helping the equations seen in section 5.2 we calculate the new population nodes and following the equations in section 5.3.2 we add them to the network following different strategies and finally we calculate the energy consumption of our proposed model.

6.3.1 Energy consmption

Like the original model, we start the operation of the network by setting the same amount of energy in all the nodes and stop the operation when the first node in exhausting its battery appears. Immediately afterwards we calculate the amount of energy remaining in the batteries.

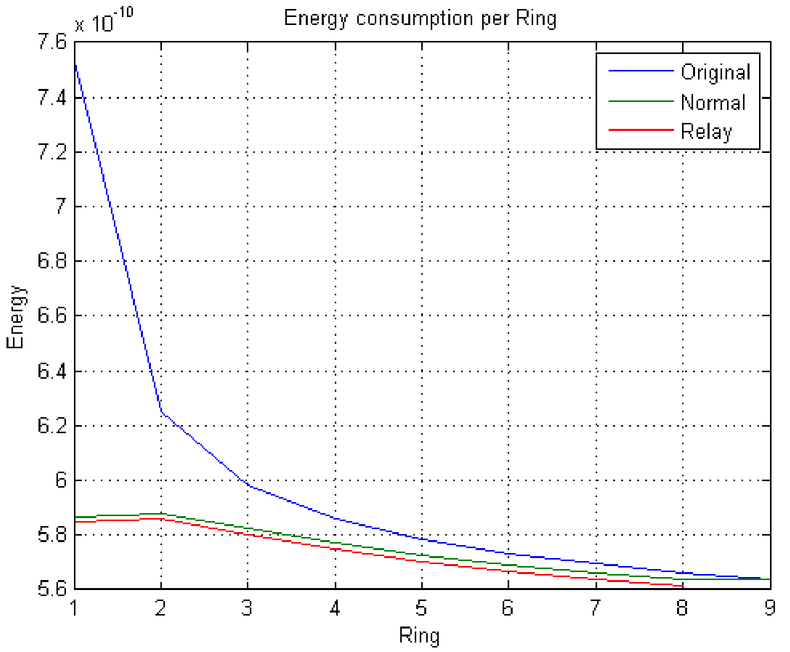


FIGURE 6.3: Typical Wireless Sensor Network.

A quick glance at the Fig. 6.3 tells us that our analysis is correct since we can appreciate a decrease in energy in the inner rings, achieving a better distribution of energy than the original model, demonstrating that it is still possible to achieve a better distribution, thus achieving, extend the useful life of the network.

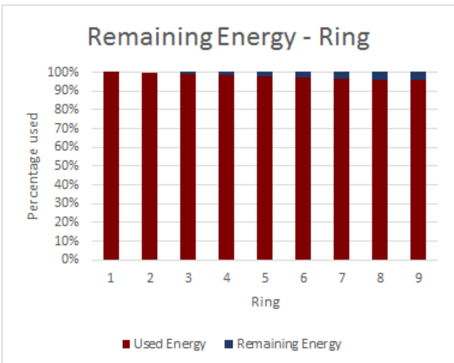
The blue line represents the energy consumption in the different rings of the network of the original model proposed by Langendoen. On the other hand, the green line shows the energy consumption of our proposed model by adding extra relay nodes. We can observe that the energy consumption between normal nodes and relay nodes is almost the same. This is because, by not transmitting any type of data, the relay nodes, red line, take part of the traffic and redirects it to the lower levels, increasing its energy consumption, While the normal nodes when sharing this percentage of traffic their energy decreases, reaching a point where the two nodes stabilize, that is why the red and green line follow the same pattern of behavior.

It can be seen that the relay deployment works. Now depending on the result of the different strategies, section 5, we have chosen the one that best achieves a balanced energy consumption and based on this result, we will compare the gain against the original model.

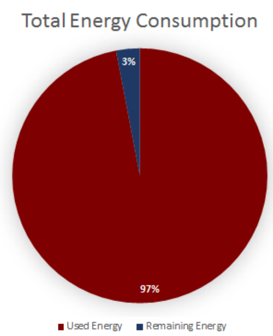
6.3.2 Remaining Energy

Once the first node in exhausting its battery appears, we analyze the remaining energy contained in the batteries of all the nodes of the network.

Figure 6.4 shows the remaining and used energy of a node in ring d, when we deploying a percentage of 20% relay nodes, following an exponential deployment strategy. Figure 6.4.a shows the energy consumed by a node in the different rings of the network. Compared to the figure, 6.2, a, we can see that the energy consumption is more balanced, allowing the nodes to consume more percentage of their battery in an almost equal proportion. This strategy has proven to increase the useful life of any node in the first ring by 28%. Figure 6.4.b, shows the total consumption of the available energy in the whole network, following the same analysis when comparing it with the original consumption, figure 6.2, b, it is clear that by achieving a better energy distribution, we have achieved an increase in the total energy consumption from 76% to 97%. In this scenario, this increment in the total energy consumption results in an increase in the useful life of the network, so it has been demonstrated that adding extra relay nodes to a wireless sensor network with a ring topology, we managed to improve the energy distribution increasing its useful life.



(a) Remaining energy per rind



(b) Remaining of the whole network

FIGURE 6.4: Remaining Energy when the network lifetime ends.

In order to better support our results, we have performed an analysis of different simulations by adding different quantities of relay nodes to the original model.

Following the idea of a better energy distribution, Figure 6.5 shows the energy consumption in the different rings of the network, for different percentages of relay nodes. At first glance we can see that at different percentages of relay nodes we achieve a better energy distribution.As we add a larger amount of relays, the energy is distributed better between all the rings and a better distribution of energy results in an increase in the lifetime of the entire network. Taking into account the number of relays needed to achieve a better energy balance, we can say that the best option is between adding 10% and 20%. From 30% onwards, it is observed that we have already reached the best energy distribution, so that by adding more relay nodes will not improve the result in this case only we will be spending resources.

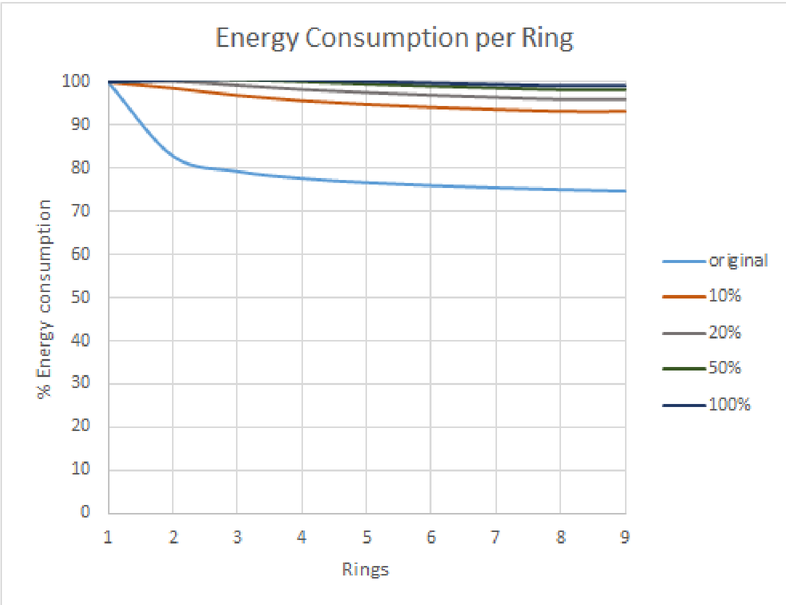


FIGURE 6.5: Distribution of energy consumption in each ring using relays

Figure 6.6 shows the behavior of the network when we add different percentages of relay nodes to increase the consumption of available energy. We can observe that as we add more relay nodes, the network consumes a higher energetic percentage. In this case, increasing the power consumption is the goal since a higher consumption, means a longer operating time, in simple words, higher power consumption means longer network life. Following the same idea, Figure 6.7 shows the percentage of additional life that we get when adding extra relay nodes. The increase of this percentage is proportional to the number of relays we add, more relay nodes means more percentage of additional life, being able to reach from 9.1

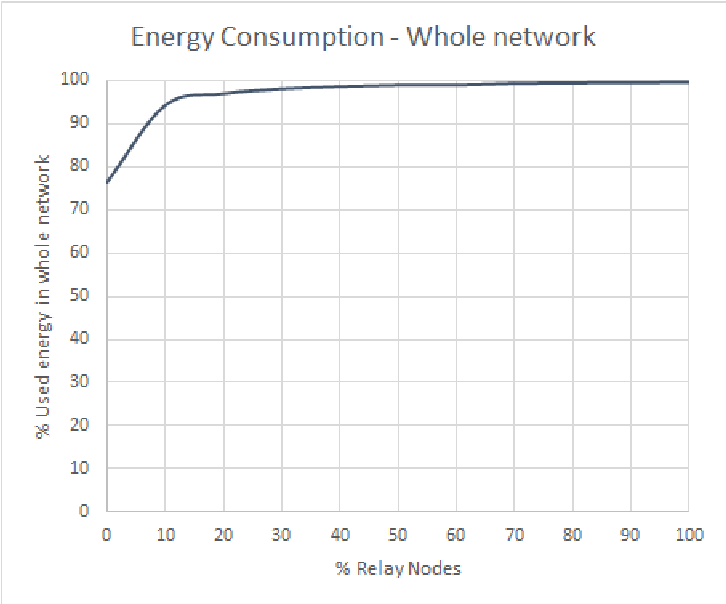


FIGURE 6.6: Energy consumption of the network using relay nodes

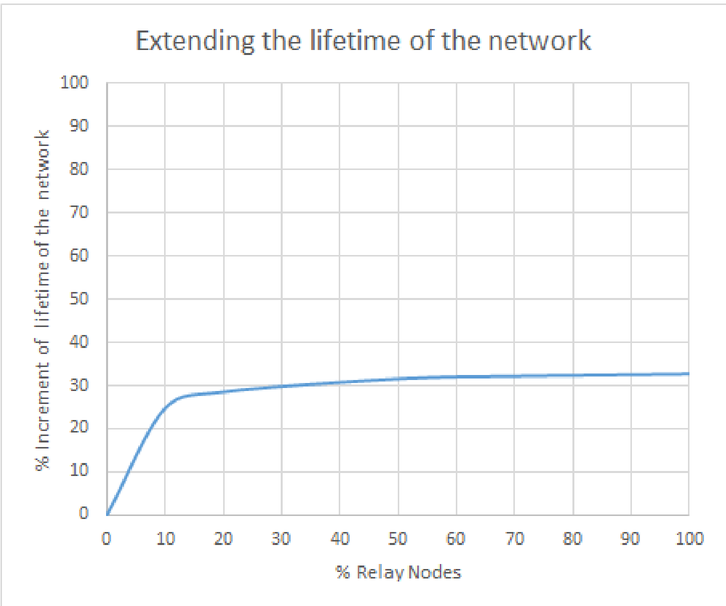


FIGURE 6.7: Extending the lifetime of the network using relay nodes

Chapter 7

Conclusions

During the development of this work we have explored the main problems in wireless sensor networks, among the most common ones we found that due to its nature characterized by the many to one traffic pattern, there is a problem of energy distribution in the different rings of the network, where we find nodes that shows little activity, mainly the nodes located in the periphery of the network, and nodes with a great amount of activity, usually the nodes located in the sections closest to the center of the network, which causes the early death of these nodes, resulting In the disconnection of a part of the network, thus reaching the end of the useful life of the network, what we commonly call the energy hole problem.

In this work, we have proposed the addition of extra relay nodes, nodes that do not generate any type of data, only take the existing traffic and help to redirect it. This type of nodes is placed at different levels of the network to help nodes with more workload, considerably increasing its lifetime in the network. To locate the best place where we will deploy these nodes we have used different strategies that include, placing the same number of relay nodes at all levels (uniform deployment) to test with different variations of the most common mathematical functions for example linear , quadratic and exponential.

Using the different forms of these functions we develop two strategies. The first was to place a large number of these nodes in the center of the network and a small number on the periphery of the network. The second was to place a small number of relay nodes in the center and a large number on the periphery of the network. Following our intuition, we found that by placing a big number of relay nodes in the center and decreasing their number in an exponential progression until reaching the last rings we achieve a better energy distribution.

Taking the results of our simulations we verified that it is possible to normalize the energy consumption in the first ring, where the nodes with the most wear are found, by allocating extra relay nodes to help them in their work to direct the incoming traffic. It was also demonstrated that the deployment of this nodes works correctly by extending the lifetime of these nodes, thus extending the lifetime of the entire network.

To summarize briefly, we can conclude the following:

- Effectively, there is an energy balance problem that can be reduced by adding an amount Nr of nodes of relay class.
- A good deployment strategy is the one that best distributes the energy between the rings allowing the network to consume the most of the energy it has available.
- The best general strategy for node relay deployment is a small number of nodes in the center of the network and a large number of nodes on the periphery of the network.
- The best deployment strategy to place a big number of relay nodes in the center and begin to decrease their number in exponential progression until reaching the periphery obtaining more nodes in the center and fewer nodes in the periphery.
- The cost of this strategy is proportional to the number of relays that we deploy in the network. A large number of relays, allows a better energy distribution and a longer lifetime, but increase the total number of nodes, therefore the cost of deployment is higher.

In addition to the ideas summarized above, the major contribution of this work is the model proposed in Section 5.2, since it can be used with other types of deployments, grid for example or any MAC protocol, being as a basis for the development of new deployment strategies.

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