UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA ELÉTRICA E INFORMÁTICA INDUSTRIAL

JOÃO PEDRO BATTISTELLA NADAS

ENERGY EFFICIENT SYNCHRONIZATION FOR ALARM DRIVEN WIRELESS SENSOR NETWORKS

DISSERTAÇÃO

CURITIBA

2016

JOÃO PEDRO BATTISTELLA NADAS

ENERGY EFFICIENT SYNCHRONIZATION FOR ALARM DRIVEN WIRELESS SENSOR NETWORKS

Dissertação apresentada ao Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial da Universidade Tecnológica Federal do Paraná como requisito parcial para obtenção do grau de "Mestre em Ciências" – Área de Concentração: Telecomunicações E Redes.

Orientador: Richard Demo Souza

Co-orientador: Sérgio Michellotto Braga

CURITIBA

2016

Dados Internacionais de Catalogação na Publicação

N129e Nadas, João Pedro Battistella
2016 Energy efficient synchronization for alarm driven wireless sensor networks = Sincronismo eficiente de relógios para redes de sensores sem fio em aplicações orientadas a alarmes / João Pedro Battistella Nadas.-- 2016.
43 f.: il.; 30 cm.

Disponível também via World Wide Web.
Texto em inglês, com resumo em português.
Dissertação (Mestrado) - Universidade Tecnológica Federal do Paraná. Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial. Área de Concentração: Telecomunicações e Redes, Curitiba, 2016.
Bibliografia: f. 40-43.

1. Energia - Consumo. 2. Sincronização. 3. Detectores. 4. Processamento de eventos (Computação). 5. Redes de sensores sem fio. 6. Sistemas de comunicação sem fio. 7. Métodos de simulação. 8. Engenharia elétrica - Dissertações. I. Souza, Richard Demo, orient. II. Braga, Sérgio Michelotto, coorient. III. Universidade Tecnológica Federal do Paraná. Programa de Pós-Graduação em Engenharia Elétrica e Informática Industrial. IV. Título. V. Título.

CDD: Ed. 22 -- 621.3

Biblioteca Central da UTFPR, Câmpus Curitiba

UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ

Câmpus Curitiba

Programa de Pós-Graduação em Engenharia Elétrica e Informática Industrial

Título da Dissertação Nº. ____

Sincronismo Eficiente de Relógios para Redes de Sensores Sem Fio em Aplicações Orientadas a Alarmes.

por

João Pedro Battistella Nadas

Orientador: Prof. Dr. Richard Demo Souza (*UTFPR*)
Coorientador: Prof. Dr. Sérgio Michelotto Braga (UFPR)

Esta dissertação foi apresentada como requisito parcial à obtenção do grau de MESTRE EM CIÊNCIAS – Área de Concentração: Telecomunicações e Redes do Programa de Pós-Graduação em Engenharia Elétrica e Informática Industrial – CPGEI – da Universidade Tecnológica Federal do Paraná – UTFPR, às 14:30**h** do dia 12 de setembro 2016. O trabalho foi aprovado pela Banca Examinadora, composta pelos professores doutores:

Prof. Dr. Richard Demo Souza
(Presidente – UTFPR)

Prof. Dr. Samuel Baraldi Mafra
(UFPR)

Prof. Dr. Guilherme Luiz Moritz
(UTFPR)

Visto da coordenação:

Prof. Jean Carlos Cardozo da Silva, Dr.
(Coordenador do CPGEI)

Este trabalho é dedicado à toda minha família. Em especial aos meus pais Christian e Beatriz, que sempre me apoiaram e me deram condições de me dedicar aos estudos e buscar o conhecimento onde fosse necessário. Também aos meu avôs, João Antônio e Peter, dos quais herdei os nomes e que sempre trabalharam muito, são para mim verdadeiros exemplos de dedicação e ética. À minha falecida avó Alfrida e à minha querida avó Helene, fontes infindáveis de carinho e amor. Aos meus irmãos não biológicos Artur, André, Ciro, Mateus e Murilo e ao meu irmão Rafael, todos sempre companheiros para discutir e compreender todas as questões, importantes ou não, da vida. E por último, mas mais importante, à minha amada esposa Jessiane, companheira para toda a vida e sem a qual nada disso teria sentido.

AGRADECIMENTOS

Gostaria de em primeiro lugar agradecer ao meu orientar Richard Demo Souza, responsável por me ensinar grande parte daquilo que é preciso para ser um bom pesquisador e quem foi do começo ao fim a pessoa mais importante para garantir que este trabalho pudesse ter sido feito. Além dele, também colaboraram enormemente meu co-orientador Sérgio Braga e meus colegas de laboratório Julio Werner e Artur Braga, com quem pude trocar idéias e chegar na forma final da contribuição. Ainda, para publicar os resultados colaboraram os professores doutores Glauber Brante e Marcelo Pellenz, aos quais sou muito grato. Agradeço também ao CPNq, à UFPR e à todos os professores e funcionários do CPGEI com quem tive contato ao longo desses 2 anos. Por fim agradeço à UTFPR, que foi minha segunda casa por mais de 10 anos.

”To find yourself, think for yourself.”

(Socrates)

RESUMO

NADAS, João P. B.. SINCRONISMO EFICIENTE DE RELÓGIO PARA REDES DE SENSORES SEM FIO EM APLICAÇÕES ORIENTADAS A ALARMES.. 44 f. Dissertação – Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial, Universidade Tecnológica Federal do Paraná. Curitiba, 2016.

Muitas aplicações de redes de sensores sem fio exigem que nós, além de monitorar certo fenômeno, devem ser capazes de detectar e comunicar eventos assíncronos (*e.g.* alarmes), o que implica que eles deverão ouvir o meio em modo ocioso, o que é inerentemente um desperdício de energia. Nesse cenário, sincronização de relógio é crucial para operar com eficiência em ciclos de trabalho e minimizar o consumo de energia. Nesta dissertação, foi avaliado o impacto do *trade-off* entre a energia gasta com sincronizações mais frequentes e, em troca reduzir a janela de escuta ociosa necessária para que a confiabilidade desejada da comunicação seja atingida. A frequência ideal de sincronizações é obtida analiticamente e corroborada por resultados numéricos, mostrando que é possível gastar uma pequena fração da energia total com uma rede com sincronização mais precisa quando comparada com a manutenção da precisão do relógio mínima exigida pelo fenômeno que está sendo monitorado, aumentando significativamente a vida útil da rede. Além disso, uma solução fechada para o limite superior a este número ideal é desenvolvida através da aproximação de que a energia gasta para transmitir ser muito menos significativa quando comparada à gasta para receber. Usando este resultado, foi possível prever através de simulações que este número ideal será aumentado pela energia de escuta, o número de vezes que um nó precisa ouvir o meio à espera de alarmes, ao nível de confiança em que o sistema foi concebido para trabalhar, ao intervalo de sincronização e à variância da frequência de oscilação relativa entre os nós. Por outro lado, este número será menor quando o custo energético de sincronização for maior (*i.e.* Quando a energia de comunicação aumentar).

Palavras-chave: Sincronismo de Relógio, Eficiência Energética, Detecção de Eventos, Redes de Sensores Sem Fio

ABSTRACT

NADAS, João P. B.. ENERGY EFFICIENT SYNCHRONIZATION FOR ALARM DRIVEN WIRELESS SENSOR NETWORKS. 44 f. Dissertação – Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial, Universidade Tecnológica Federal do Paraná. Curitiba, 2016.

Many applications of wireless sensor networks require that nodes, besides monitoring a given phenomenon, must be able to detect and communicate asynchronous events (*e.g.* alarms), implying that they have to often listen to the medium in idle mode, which is inherently energy wasteful. In such a scenario time synchronization is crucial to efficiently operate in duty-cycles and minimize energy consumption. In this work we assess the impact of the trade-off between spending energy with more frequent synchronizations and in return saving it by reducing the idle listening window necessary for the desired reliability of the communication. The optimal frequency of time synchronizations is obtained analytically and corroborated by numerical results, showing that several times less overall energy may be spent with a finer synchronization when compared with maintaining the minimum clock precision required by the phenomenon being monitored, greatly extending the life-span of the network. Furthermore, a closed form upper bound to this optimal number is derived by approximating transmit power being of much more significance when compared to receive power. Using this result, we predict and then simulate that this optimal number will be increased by the listening power, the number of times which a node has to listen to the medium idly, the level of confidence at which the system is designed to work, the synchronization interval and the variance of the relative oscillation frequency between synchronizing nodes. On the other hand, this number will be smaller when the energy cost of synchronization is higher (*e.g.* when active communication energy increases).

Keywords: Clock Synchronization, Energy Efficiency, Event Detection, Wireless Sensor Networks

LIST OF FIGURES

LIST OF ACRONYMS

FTSP	Flooding Time Synchronization Protocol
GPRS	General Packet Radio Service
GPS	Global Positioning System
LME	*Laboratório de Monitoramento Eletrônico*
LTS	Lightweight Time Synchronization
MAC	Media Access Control
NTP	Network Time Protocol
RBS	Reference Broadcast Synchronization
STS	Simple Time Synchronization
UFPR	*Universidade Federal do Paraná*
w.r.t.	with respect to
WSN	Wireless Sensor Network

LIST OF SYMBOLS

T	Synchronization interval
σ_f^2	Variance of the relative clock skew
σ_τ^2	Variance of the propagation delay
σ_θ^2	Variance of the relative offset
T_s	Maximum synchronization interval
$\bar{t}_w$	Average waiting time
β_0	Probability of listening to the synchronization beacon
K	$Q^{-1}(1-\beta_0)$
Q^{-1}	Inverse Q-function
t_g	Guard time
t_a	Advance time
t_w	Waiting time
N	Optimal number of synchronization beacons
n	Real relaxation of N
P_l	Idle listening power
P_s	Transmitting power
T_b	Beacon duration
P_{sync}	Total synchronization power
P_r	Receiving power
p	Number of equally spaced idle listening windows within every T_s
E_{idle}	Idle listening energy
M	Number of synchronizations within T_s
E_{sync}	Synchronization energy
E	Total energy
$m^\star$	Optimal amount of synchronizations within T_s, in terms of energy efficiency
m	Real relaxation of M
$M^\star$	Closest integer value to $m^\star$
m_b	Upper bound of $m^\star$
η	Gain of the proposed strategy

CONTENT

1 INTRODUCTION

Wireless Sensor Networks (WSNs) consist of sensor nodes deployed in order to monitor phenomena of interest (AKYILDIZ et al., 2002b). With the devise of cheaper radio modules as well as sensors and batteries, WSNs gained rapid popularity (AKYILDIZ et al., 2002a) and have been used in different areas with the intent of automation, monitoring or detecting events and raising alarms (GOLDSMITH; WICKER, 2002). One important aspect of WSN nodes is that very often they must have their clocks synchronized. This is useful not only for application specific purposes, but also for efficient channel access (LI; RUS, 2006). Many synchronization protocols can be found in the literature; (GANERIWAL et al., 2009) present a broad bibliographic research on efficient synchronization protocols, such as the Flooding Time Synchronization Protocol (FTSP) (MARÓTI et al., 2004), the Reference Broadcast Synchronization (RBS) algorithm (ELSON et al., 2002), the Simple Time Synchronization (STS) (SICHITIU; VEERARITTIPHAN, 2003) and the Lightweight Time Synchronization (LTS) methods (GREUNEN; RABAEY, 2003). All these approaches have one primary focus: increasing synchronization precision.

Since the nodes are usually disposable and powered by batteries, another important goal in the design of a WSN is that it must be energy efficient (ANASTASI et al., 2009). With that in mind, the Guard Beacon scheme has been recently proposed in (CHEN et al., 2014), focusing on optimizing the energy used on clock synchronization, as opposed to clock precision. Guard Beacon is based on using any established synchronization protocol, but reducing the idle listening window by sending synchronization beacons multiple times at optimal instants, which may result in more than 40% of savings in synchronization power consumption.

However, a relevant scenario not considered in (CHEN et al., 2014) is the possibility of the nodes detecting and communicating asynchronous events, such as alarms. In order to be able to receive alarms, the nodes must listen to the channel idly following a given pattern. Alternatively, the nodes could use a wake up radio (DEMIRKOL et al., 2009), wherein a simpler energy inexpensive radio is always listening just for the alarm propagation. However, compared with usual radio modules, state of the art wake up radios have a poor sensitivity (DONNO et al., 2014) resulting in short communication ranges, which may be insufficient for many applications.

1.1 MOTIVATION

This work has been developed in a partnership with the *Laboratório de Monitoramento Eletrônico* (LME) of the *Universidade Federal do Paraná* (UFPR) and the motivation was an application of a WSN (NADAS et al., 2015) with sparsely spread nodes to monitor information of the hydrological reservoir of Vossoroca, situated near Curitiba. The distance between two nodes of this WSN is of the order of kilometers and thus the communication is energy expensive. The proposed network has the intent of monitoring hydrological and meteorological aspects regarding the reservoir in order to facilitate limnological (WETZEL, 2001) research related to the site.

Among the parameters measured stand out the temperature of the water in different depths and spatial positions, air temperature, the level of the affluent rivers and the level of the reservoir itself. Additionally, let us remark that the samples acquired by different nodes will later be joined together in order to validate hydrological models. Thus, it is of high importance that the clocks of the nodes are synchronized. Furthermore, the parameters being measured have slow variation in normal conditions, and thus a slow sampling period (15 minutes) is sufficient at most times. It is desirable to keep this slow sampling in order to save storage and energy. However, during some particular events, the parameters changing rate may vary and a faster sampling period is desirable (1 minute), hence, when a node detects an event, it must alert other nodes to increase their sampling frequency, enabling a better understanding of the changes promoted by the event.

The Vossoroca reservoir WSN is also applied in order to properly study the effect of diffused pollution on the water body. Diffuse pollution is characterized by the entrance of pollutants from the land adjacent to the water body that enters the lake during precipitation events (NOVOTNY, 2003). Thus, the WSN must be able to trigger the collection of water samples during extreme precipitation events, which will be done by using modified SBn equipments (BRAGA, 2013). SBn equipments consist of pumps that can collect and store many samples of water when there is a rapid variation in level of a water body, which usually mean a precipitation event. The modification that will be done in the equipments consist of having the triggering event being communicated through the WSN instead of having the level sensor directly attached to it. Thus, it is possible to acquire water samples throughout the entire precipitation event, starting to collect water samples as soon as the water from the rain that fell on the side of the reservoir is reaching the lake, which is valuable to the study of diffuse pollution (PIONKE et al., 2000).

Figure 1 shows the described Vossoroca reservoir WSN, which is composed of some nodes equipped with data loggers, batteries, solar panels for energy repletion, SBn equipments and radio modules. A meteorological station (connected to the grid) near the reservoir acts as a sink node and communicates with the internet via General Packet Radio Service (GPRS). The nodes close to the border of the reservoir are triggered via signal propagated from the network and start collecting water samples when a large precipitation event is detected, either via increase in the level of the affluent river or via the meteorological station, which is equipped with a pluviometer.

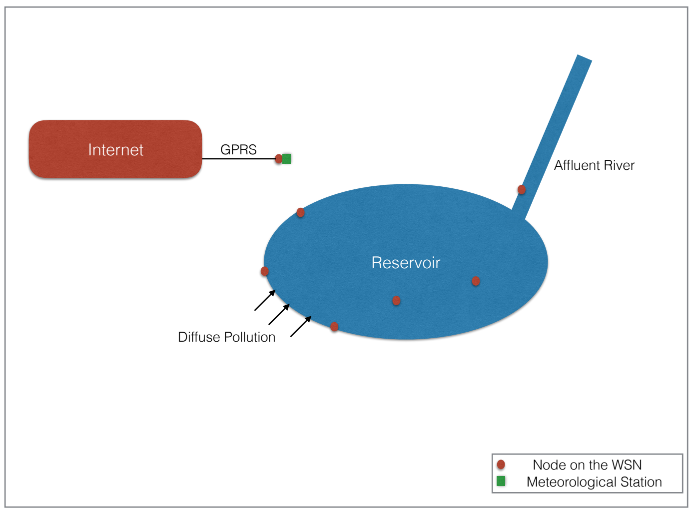

Figure 1: The proposed WSN to monitor the Vossoroca reservoir.

It is important to point out that, even tough the nodes are equipped with a solar panel to perform energy harvesting from the medium, long periods without or with low incidence of sunlight may occur. Thus, in order for the network to remain operational at all times, it is crucial that it is energy efficient. In addition, as mentioned before, the nodes must keep their clocks synchronized. Motivated by these two factors, this work has been devised in order to provide a more energy efficient synchronization protocol given that alarms will be propagated through the WSN.

1.2 OTHER ALARM DRIVEN APPLICATIONS

Many other WSN applications also have similar alarm characteristics. For instance, in (LEE et al., 2010), a WSN is proposed to monitor debris flow in water flowing downslopes and propagate a warning signal through the network in order to alert and prevent damages. Also, in (GUTIÉRREZ et al., 2014) a WSN is used to monitor soil moisture and temperature in crops and, when a predefined threshold is reached, propagate an alarm that triggers actuators to, for instance, start irrigation. Furthermore, in (LEE et al., 2012) a WSN is deployed on the surroundings of an emergency repair work and monitors the level of pollution on that area in order to signal an alarm in case these levels become too high.

In addition, the importance of being able to communicate alarms in a WSN can also be illustrated in many other environmental monitoring applications, wherein usually the physical quantities being monitored have a slow variation (PIONKE et al., 2000; ZHAO et al., 2009), and thus only a few spaced samples are required by the monitoring application and detecting an event can be of great value. For instance, (PIONKE et al., 2000) determined that 90% of the phosphorus available in the Cheasapeake river basin was on average transported by the seven largest precipitation events every year. Hence, in order to study this hydrological phenomena it is important to identify such extreme events in order to accurately sample the most relevant physical quantities. Another related application is in forest fire detection (ZHAO et al., 2009), where the WSN operates with a low duty-cycle and eventually must propagate alarms to warn about a potential fire. Similar cases, including slow sampling applications and potential alarms between sampling rounds, have been investigated for instance in (GRILO et al., 2007; URTE-AGA et al., 2009; SHAQADAN; AL-RAWASHDEH, 2014).

In all of the above applications, sensors can operate with a sow sampling rate and a coarse time synchronization in order to save energy and storage space. However, important phenomena may occur in a short time period and in order to adequately monitor that event, or send out a warning about it, it is crucial to identify the event and distribute an alarm along the network. Additionally, as it has already been discussed, having an energy efficient WSN is always desirable. Therefore, this work focuses on optimizing energy efficiency in WSNs to be used in alarm driven applications.

1.3 OBJECTIVE

1.3.1 GENERAL OBJECTIVE

The objective of our work is to propose a novel strategy for clock synchronization extending the work of (CHEN et al., 2014) considering WSNs used in alarm driven applications with coarse synchronism requirements, such as the ones presented in Section 1.2. The proposed novel strategy has been recently published in (NADAS et al., 2016). The idea focuses on increasing energy efficiency by reducing overall energy waste by using a strategy aimed at shortening idle listening time, based on the fact that one of the major sources of energy waste on a WSN is in fact idle listening (YE et al., 2006).

1.3.2 SPECIFIC OBJECTIVES

Our goal can be achieved by finding an optimal synchronization for the WSN, given the periodicity of the alarms and the minimum precision required by the phenomena. We analyse the trade-off between the energy spent with more frequent synchronizations and the energy saved by reducing idle listening time. Nodes may communicate with a low duty-cycle (ANASTASI et al., 2009), waking up at scheduled instants and for a predetermined amount of time, so that messages (or alarms) can be detected with a given success probability. The coarser the time synchronization, the larger must be the duration of the idle listening window to guarantee that a given message is detected, thus increasing the energy consumption. On the other hand, a finer time synchronization guarantees a shorter idle listening window, reducing the energy consumption for messages or alarm detection, but increasing the energy necessary for time synchronization.

1.4 DOCUMENT STRUCTURE

The rest of this document is organized in four more chapters. Chapter 2 provides the theoretical contextualization of this work, containing a description of WSNs, the importance of time synchronization in WSN applications and describing some strategies of clock synchronization. In addition, a discussion is risen regarding the importance of energy efficiency in WSNs, as well as some strategies to increase it, in particular related to duty-cycling. Chapter 3 lays out the model of the system that is going to be the base of the work and proposes a method for finding the optimal amount of synchronization rounds for alarm driven applications. Furthermore, an upper bound to this number is found when considering the energy spent on the receiver being much less significant than the one spent on the sending node. Chapter 4 presents the numerical results. First computer simulations are made to verify the validity of the optimization performed in the previous chapter, then variations of the parameters are analyzed showing their influence. The gain in terms of energy is computed, being several orders of magnitude lower than the spent using the traditional approach. Chapter 5 provides the conclusions and finishes with a suggestion of three possible extensions.

2 THEORETICAL CONTEXTUALIZATION

2.1 WIRELESS SENSOR NETWORKS

WSNs consist of a large number of sensing nodes that communicate with each other and are deployed in order to monitor certain phenomena (AKYILDIZ et al., 2002a). The reduced price of low power radios and microprocessors has spurred the application of WSNs in a wider range of scenarios (AKYILDIZ et al., 2002a). On the military, WSNs are used in different ways (GOLDSMITH; WICKER, 2002), as first line of detection for different kinds of attacks, to track possible targets, among other uses. In industrial environments WSNs are deployed to monitor hazardous locations (GOLDSMITH; WICKER, 2002) such as nuclear power plants or mines. Civilians also benefit from WSNs. Sensors can monitor parameters of a home environment ensuring the safety of elderly people (WOOD et al., 2006). Moreover, environmental monitoring provides a large array of possible applications, as the tracking of forest fires (ZHAO et al., 2009), disaster prevention (LEE et al., 2010, 2012), sensing the presence of pollutants (NADAS et al., 2015), automated crop irrigation (GUTIÉRREZ et al., 2014) and many other possibilities.

Topologies may vary from application to application, but usually the network is organized as a dense cloud of sensors deployed over the area of interest with some nodes being sink nodes, which are usually externally connected and can interface with other types of networks (*i.e.* the internet) (ANASTASI et al., 2009).

One of the most important design constraints when devising a WSN is energy efficiency. This is due to the fact that, depending on the fault tolerance of the network, it may not be able to sustain its operations when a certain amount of nodes consume their batteries. Fault tolerance, or reliability, is a measure of the resilience of the network, in other words, how well can it sustain its operation when a node fails due to malfunctioning or loss of power. The reliability of the network follows a poison distribution that depends on the failure rate of the sensor nodes (HOBLOS et al., 2000). However, it is important to point out that even tough a network might have a high reliability, it will still benefit on the long term from energy efficiency, since it will be able to sustain its operation for a longer time (ANASTASI et al., 2009).

2.2 ENERGY EFFICIENCY IN WIRELESS SENSOR NETWORKS

Since in WSNs the nodes operate on batteries that in most cases will not be replaced, the lifetime of the network is determined by the amount of energy the nodes have stored (GOLDSMITH; WICKER, 2002). Hence, it is crucial that WSNs be energy efficient, in other words, they must be able to complete the same task using the least amount of energy possible, that is why each specific use of WSNs may apply different strategies to save energy while still performing the task it has been designed for (RAULT et al., 2014). The manners by which WSNs can save energy can be divided into five main categories (RAULT et al., 2014):

1. Radio optimization: Improving the efficiency of the physical layer of the communication. This can be done in many different ways, as for instance via the use of directional antennas, cooperative communication (MEULEN, 1971; LANEMAN, 2006), as in (BRANTE et al., 2011) or coding, as in (ROSAS et al., 2016).

2. Data reduction: Applying methods to reduce the amount of data being communicated, thus reducing the energy spent on communication. Examples of this are data aggregation - where nodes on a path towards the sink join information by performing some operation, as in (AL-KARAKI et al., 2004) -, adaptive sampling - sensors increase their sampling frequency during the occurrence of events of interest, as in (NADAS et al., 2015) - or data compression, as in (MARCELLONI; VECCHIO, 2008).

3. Energy efficient routing: Routing protocols can greatly impact the energy cost of communicating a message from one node to another, or from a leaf node to a sink node. In (PANTAZIS et al., 2013) a broad survey on energy saving routing protocols for WSNs is presented.

4. Battery repletion: Refilling the batteries with energy might be one possible solution to improve network lifetime. This can be done through harvesting the energy from the medium, as in (NADAS et al., 2015), or from the communication itself (AUER et al., 2011), as in (MORITZ et al., 2014).

5. Duty-cycle: Reducing the amount of time that nodes listen idly to the medium will reduce energy waste in WSNs (YE et al., 2006). Because in alarm driven applications nodes will inherently have to idly listen to the medium, we propose an idea involving duty-cycling in order to gain energy efficiency.

2.2.1 DUTY-CYCLING

Duty-cycling is an important technique for improving energy efficiency in WSNs, mainly because it may reduce drastically idle listening times. Some strategies of duty-cycling are presented in (RAULT et al., 2014) and are divided into three types: wake-up radio (DEMIRKOL et al., 2009), scheduled *rendez-vous* (ANASTASI et al., 2009) and asynchronous.

The wake-up radio techniques consist of an energy inexpensive radio being awake all the time to receive a signal before the communication can be established, then the node wakes up the main radio that is capable of sustaining the application required needs (*i.e.* bandwidth) and when the communication finishes the main radio returns to sleep mode. The problem with this strategy is that state of the art wake-up radios have short ranges due to their poor sensitivities (DEMIRKOL et al., 2009), which might invalidate this option depending on particular network topology.

The scheduled *rendez-vous* strategy is based on the premiss that communication will only occur at pre determined instants. Nodes wake up only at scheduled times, and their neighbours will also be awake and perform communication. The clocks of the nodes must be synchronized in order for this method to work properly, so neighbouring nodes will wake up at the same instants and communicate accordingly.

The asynchronous method works by nodes waking up periodically and checking if there is information being transmitted. It is similar to the scheduled *rendez-vous* method but with the advantage of not requiring clock synchronism. However this may be energy inefficient if a large number of messages are being exchanged because the transmitter has to wait for the receiver to be awake in order to send its signal. Most WSNs will have clock synchronism by default and there is no advantage in using the asynchronous method over the scheduled *rendez-vouz* if the clocks are already synchronized. Furthermore, it is possible to optimize clock synchronism in order to perform scheduled *rendez-vous* duty-cycling to check for unexpected signals (*i.e.* alarms) greatly saving energy, as is the case of the work presented herein.

2.3 TIME SYNCHRONISM

Since nodes commonly use crystals to count time, which have distinct oscillation frequency drifts, there is an inherent difference in the time measured by clocks of two nodes at a given time (WU et al., 2011). An ideal clock counts time as

$$C(t) = t \tag{1}$$

(WU et al., 2011), where C is the clock's counting time and t is the ideal time. However, since no clock is ideal, a clock will measure time, relative to another as

$$C(t) = ft + \tau \tag{2}$$

where f is the relative oscillation frequency between the clocks, or skew, and τ the accumulated offset. Two nodes are considered synchronized when $\tau = 0$.

In a classical synchronization scenario, every T seconds (synchronization interval) the nodes will synchronize their clocks in order to maintain a certain level of precision, required by the application. Clock synchronism is used in WSNs for many different reasons. For instance, in order to perform data fusion - combine samples acquired in different locations and time instants to gather meaningful information - the clocks of the nodes must be synchronized (WU et al., 2011). Power management through duty cycling is improved greatly if clock synchronism is performed (WU et al., 2011).

Popular clock synchronization strategies include the Network Time Protocol (NTP) (MILLS, 1992) or the Global Positioning System (GPS) (HOFFMAN et al., 1997). However since nodes on a WSN will not always be capable of performing those kinds of synchronizations because of lack of hardware, energy or connectivity constraints, they will not be considered for the rest of this work.

In the following subsections, we will be presenting three different time synchronism strategies that are suitable for WSNs.

2.3.1 SIMPLE TIME SYNCHRONIZATION

The STS method, presented in (SICHITIU; VEERARITTIPHAN, 2003), is a time synchronization protocol which is based on frequently adjusting f and τ when regular communication occurs. In a scenario where a node (A) wishes to determine $C(t_B)$, its clock relative to node B, node A sends a beacon to node B timestamped with t_o. Node B timestamps the message with t_b and returns it immediately. Finally, node A receives back the beacon and promptly timestamps it with t_r. A data-point is formed by a set of (t_o, t_b and t_r) and the following inequalities are generated:

$$t_o < ft_b + \tau; \tag{3}$$

$$t_r > ft_b + \tau. \tag{4}$$

The data-point is then stored by node A and a second round of communication happens. A second data-point is generated and, solving the four inequalities it is possible to have an estimate of f and τ with which node A corrects its clock on every tick. Every time a new beacon is sent, a different data-point is generated and there are two possible alternatives: keep all the data points, increasing considerably the precision of the estimation as well as the complexity of the mathematical programming problem, or discard the less restrictive data points and compromise on the precision, but keep the problem simple. Because of limited computational power and limited energy constraints on WSNs, the later is preferred in most cases involving such networks.

This idea is interesting in WSN applications where communication occurs often and the timestamps can be included into headers without much overhead. That is because in such scenario, many data-points are generated and the estimate will be sharper. However, in applications where communication is sparsely spread, the algorithm will not perform so well due to the scarcity of data-points.

2.3.2 LIGHTWEIGHT TIME SYNCHRONIZATION

The LTS scheme has been proposed for WSNs in (GREUNEN; RABAEY, 2003) and consists of a protocol for time synchronization designed to be light, being a good fit to be applied on WSNs with limited resources, such as computational power or energy. Two types of synchronization are proposed, the first one being applied to pair-wise synchronization and the later designed as a centralized multi-hop synchronization.

In the pair-wise scenario, node A will synchronize its clock to node B's clock. This is done by node A sending a synchronization beacon timestamped with its measure of time at that instant t_1. Node B receives it at

$$t_2 = t_1 + \tau + \theta \tag{5}$$

where θ is the transmission time. Then node B sends another packet of information containing the values of t_1 and t_2, timestamped with its time t_3, that arrives at node A's time $t_4 = t_3 - \tau + \theta$, which then calculates τ by subtracting t_4 from t_2, yielding

$$\tau = 0.5(t_2 - t_4 - t_1 + t_3). \tag{6}$$

Node A then compensates the offset and the clocks are synchronized.

The error in the synchronization can be characterized by accounting for the difference in the value of θ for both transmissions, which is composed of the propagation delay, the send time, the receive time and the access time.

The propagation delay is deemed unknown and it is a function of the distance, which is assumed not to vary rapidly, thus does not contribute significantly to the error in the synchronization. The send time is the time spent preparing the message and since the message is timestamped after this operation, does not contribute to the error.

The receive time related to the processing of the received message, it can vary with a Gaussian distribution with zero mean and variance σ^2. The access times differ in the same way as the receive times do, because of the fact that the packets of information used in Media Access Control (MAC) have to undergo the same physical and MAC layers of the radio, therefore it is assumed that it also follows a Gaussian distribution with zero mean and variance σ^2. Hence, the total error in this pair-wise synchronization will be Gaussian with variance at most four times σ^2, assuming no correlation between receiving times and access times of both nodes.

The centralized multi-hop is an extension of the pair-wise synchronization. It is assumed that one node in the WSN has the correct time and all other nodes will synchronize their clocks to this node's. The algorithm consists of the main node sending the synchronism signal to their immediate neighbours, that will synchronize their clocks and then send a signal to its neighbours that are unreachable from the main node. The depth of the node in this scheme is determined by the number of pair-wise synchronizations that had to be performed in order to become synchronized. The process is repeated until all nodes in the network are synchronized.

In the centralized multi-hop approach, errors will accumulate with each pair-wise synchronization and the further a node is from this master node, the greater its error will be. Since the pair-wise errors are considered to be independent random variables, the error for a node with depth i will be Gaussian with zero mean and variance $4i\sigma^2$.

2.3.3 GUARD BEACON

The Guard Beacon (CHEN et al., 2014) scheme differs from most clock synchronization protocols because its main focus is on saving energy. Let us recall that, in the usual scenario, when two nodes wish to synchronize their clocks, node A sends a beacon to node B containing the time with respect to (w.r.t.) A's clock. Moreover, a clock instant w.r.t. node B can be related to an instant w.r.t node A using the propagation delay and the relative oscillation and offset of the clocks using (2). In order for node B to synchronize its clock with node A, it must estimate such parameters and correct its clock accordingly, which can be performed by plenty of well established methods, such as the already presented LTS and STS.

Considering that just after each synchronization the error between the clocks is zero, before each synchronization round the accumulated error between the two clocks can be expressed as a random variable that follows a Gaussian distribution with zero mean and standard deviation

$$\sigma_e = \sqrt{T^2\sigma_f^2 + \sigma_\tau^2 + \sigma_\theta^2}, \quad (7)$$

where σ_f^2 is the variance of the relative clock skew, σ_τ^2 is the variance of the propagation delay and σ_θ^2 is the variance of the relative offset.

Let us assume that the particular application demands certain precision among clocks, which imposes a maximum synchronization interval T_s, and therefore $T \leq T_s$. The idea behind Guard Beacon is to minimize the overall energy spent during synchronization, by sending more than a single beacon, which in turn reduces the average waiting time $\bar{t}_w$. Figure 2 represents how the proposed scheme minimizes $\bar{t}_w$ by considering that the clock error is Gaussian. The probability β_0 of listening to the synchronization beacon is then determined by the probability of the node being awake at the time the beacon is sent.

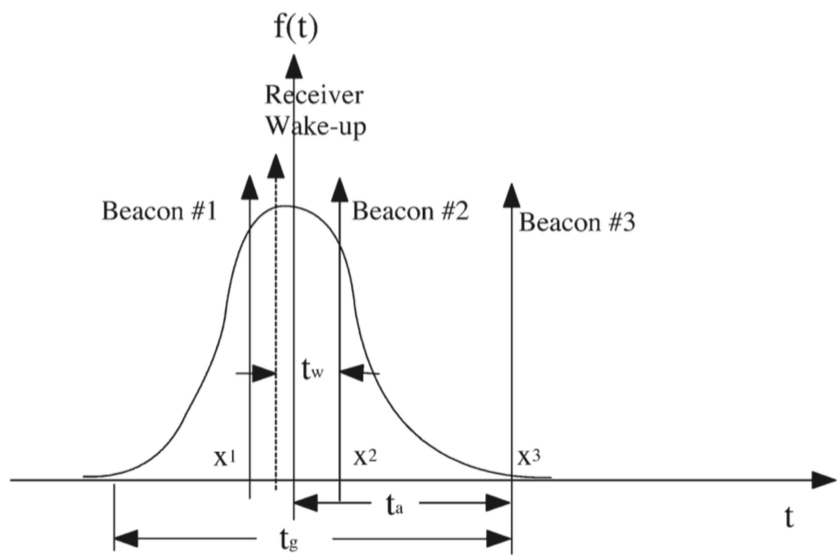

Figure 2: Representation of the beacon waiting time of Guard Beacon. (CHEN et al., 2014)

Thus, to ensure β_0 node B must wake up

$$t_a = K\sigma_e \quad (8)$$

seconds in advance – this is denoted advance time –, where $K = Q^{-1}(1-\beta_0)$ and Q^{-1} is the inverse Q-function. Node B then listens to the medium for at least a guard time $t_g = 2\,t_a$ before sleeping again. The duration from the moment B wakes up to the instant it catches a beacon is

t_w. If the beacon is missed, node B doubles t_g for the next round as part of a synchronization recovery strategy (CHEN et al., 2014), otherwise it calibrates its clock and resumes sleeping.

In (CHEN et al., 2014) methods for determining N, the optimal number of synchronization beacons, as well as the optimal instants to send them, are presented. Note that since the exact solution does not have a closed form, a tight approximation for N is presented in (CHEN et al., 2014)

$$N \approx n = \sqrt{\frac{t_a P_l}{T_b P_s}}, \tag{9}$$

yielding an average waiting time of

$$\bar{t}_w \approx \frac{t_a}{n}, \tag{10}$$

where $n \in \mathbb{R} \,|\, n \geq 1$, P_l and P_s are the idle listening and transmitting powers, respectively, and T_b is the beacon duration. Moreover, in order to obtain the above results, the total power spent on synchronization P_{sync} is optimized, in other words,

$$P_{\text{sync}} = \frac{\bar{t}_w P_l}{T} + \frac{T_b}{T} P_r + \frac{N T_b}{T} P_s, \tag{11}$$

is minimized given a probability of the node being awake to listen to at least one beacon, where P_r is the receiving power.

3 DEVELOPMENT

3.1 SYSTEM MODEL

3.1.1 LOW DUTY-CYCLE ALARM-DRIVEN WSN

Let us now extend the scenario of Guard Beacon (CHEN et al., 2014) presented in Section 2.3.3 to the possibility of detecting and propagating asynchronous events between each T_s, specially for relatively large T_s. In this scenario, large synchronization intervals imply a large value of t_g to guarantee β_0 probability of beacons (be them for synchronization or alarm purposes) being detected. This also increases the cost of idle listening increasing the energy consumption (YE et al., 2006).

Considering p equally spaced idle listening windows within every T_s with the purpose of communicating alarms, our goal is to determine the optimal synchronization frequency in terms of energy efficiency. The choice of p depends on the particular application and phenomena being monitored. Note that our scenario reduces to that of (CHEN et al., 2014) if $p = 0$, because the possibility of alarms propagation is not accounted for in (CHEN et al., 2014). In principle our goal can be achieved by reducing t_g through synchronizing the nodes more often ensuring a finer clock synchronization and reducing overall energy consumption. Furthermore, it is important to point out that over-synchronizing may not be efficient, since too much energy might be wasted with more frequent synchronizations[1] . Hence, based on this trade-off, the idea is to determine the optimal number of times to synchronize every T_s seconds in order to balance the energy spent idly listening (E_{idle}) and the energy spent to perform $M \in \mathbb{N}^*$ synchronizations (E_{sync}) within T_s. Thus, we minimize the total energy E by reducing t_g at the cost of increasing M, which can be formulated as

$$\min_M E = E_{\text{sync}} + E_{\text{idle}}, \tag{12}$$

where E_{sync} is composed of the energy spent receiving the beacons, the energy spent waiting

[1]Note that the synchronization and alarm listening windows cannot be the same as in a general scenario the node sending an alarm may not be the master node that sends the synchronization beacons, and a collision could occur.

for the beacons and the energy spent transmitting beacons, so that

$$E_{\text{sync}} = M\left(\bar{t}_w P_l + T_b P_r + N T_b P_s\right), \tag{13}$$

whereas

$$E_{\text{idle}} = p\,t_g P_l = 2p\,P_l K \sigma_e. \tag{14}$$

Moreover, in this novel scenario, (7) must be rewritten as

$$\sigma_e = \sqrt{\left(\frac{T_s}{M}\right)^2 \sigma_f^2 + \sigma_\tau^2 + \sigma_\theta^2}. \tag{15}$$

Note that when $M = 1$ and $T = T_s$ we have the same baseline scenario considered in (CHEN et al., 2014).

The basis of the proposed optimization is illustrated in Figure 3, where $p = 4$ idle listening windows are considered (in green). The first scenario illustrated at the top of the figure represents the baseline scenario, with $M = 1$ (in blue), $N = 4$ beacons and a guard time of $t_g = 15$ ms being necessary to ensure a β_0 target probability of a beacon being captured. At the bottom of the figure, a second scenario with $M = 3$ is shown, in which only $N = 2$ beacons and $t_g = 6$ ms are necessary. Thus, even with the cost of three times more frequent synchronizations, the total energy consumption in the second scenario may be less than in the first, as N and t_g decreased. Next, we present closed form equations that allow the optimization of M in terms of energy.

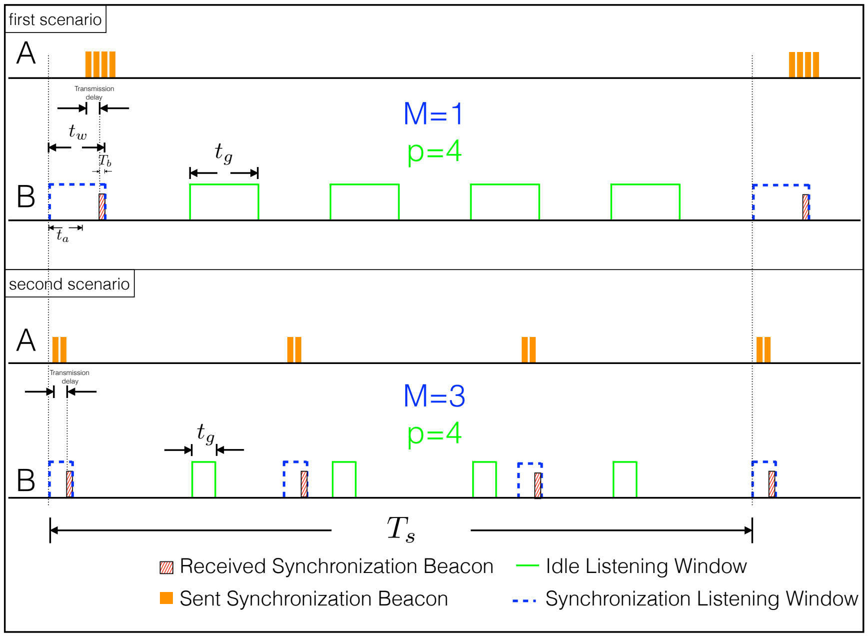

Figure 3: Proposed scheme reducing the idle listening window (t_g) while increasing the number of synchronizations (M) within a time interval T_s. (NADAS et al., 2016)

3.2 OPTIMIZATION

Theorem 1. *The optimal amount of times* $m^\star$ *– in terms of energy efficiency – to synchronize nodes on a WSN, wherein each node idly listens to the medium* p *times waiting for alarms between each maximum synchronization interval* T_s*, can be very well approximated by the real positive solution of*

$$T_bP_rm^2 + \sqrt{T_bP_sP_lKT_s\sigma_f}m^{\frac{3}{2}} - 2pP_lKT_s\sigma_f = 0, \tag{16}$$

w.r.t. m*, given that* $8pN > m$ *and where* $m \in \mathbb{R}^+$.

Proof. First, combining (13) and (14) we arrive at

$$E(M) = M(\bar{t}_w(M)P_l + T_bP_r + N(M)T_bP_s) + pt_g(M)P_l, \tag{17}$$

then given that $n \approx N$ and using (10) we can write

$$E(M) = M(\frac{t_a}{n}P_l + T_bP_r + nT_bP_s) + pt_gP_l. \tag{18}$$

Applying (9) and the relation $t_g = 2t_a$ into (18) yields,

$$E(M) = M\left(\sqrt{t_a P_l T_b P_s} + T_b P_r + \sqrt{t_a P_l T_b P_s}\right) + 2pP_l t_a \tag{19}$$

Finally, combining the terms, (19) can be rearranged into

$$E(M) = M\left(2\sqrt{T_b P_s P_l t_a(M)} + T_b P_r\right) + 2pP_l t_a(M). \tag{20}$$

Moreover, when $\left(\frac{\sigma_f T_s}{M}\right)^2 \gg \sigma_\tau^2 + \sigma_\theta^2$, which is tight for $T_s > 100$ seconds and typical values of the variances, it is possible to approximate (15) well and apply it to (8), so that

$$t_a(M) \approx \frac{K T_s \sigma_f}{M}, \tag{21}$$

which is tight when the maximum synchronization interval T_s is large [2]. Replacing M in (20) by $m \in \mathbb{R}^+$,

$$E(m) = m\left(2\sqrt{T_b P_s P_l t_a(m)} + T_b P_r\right) + 2pP_l t_a(m), \tag{22}$$

which is a function to be minimized w.r.t. m. Next, the optimum m can be found if $E(m)$ is a convex function. In this case, $\frac{\mathrm{d}^2 E(m)}{\mathrm{d}m^2} > 0$ must hold, so that

$$\frac{K T_s \sigma_f t_a(m)\left(8pP_l\sqrt{t_a(m)} - m\sqrt{P_l P_s T_b}\right)}{2\left(m\sqrt{t_a(m)}\right)^3} > 0 \tag{23}$$

is to be satisfied. Note that since m, as well as all the constants, can only assume positive values, (23) can be simplified to

$$8pN > m, \tag{24}$$

which is the condition to assure convexity. For the practical system parameters considered in this work $m^\star$ always lies within the interval in which $E(m)$ is convex. However, if for other system parameters - for example if T_s is very large and p is small - this condition is not met, $m^\star$ can be found through other forms of optimization, such as a heuristic approach (LEE; EL-SHARKAWI, 2008).

Finally, the optimum can be found by solving $\frac{\mathrm{d}E(m)}{\mathrm{d}m} = 0$, which can be written as

$$2\sqrt{T_b P_s P_l}\left(\sqrt{t_a} + \frac{m}{2\sqrt{t_a}}\frac{\mathrm{d}t_a}{\mathrm{d}m}\right) + T_b P_r + 2pP_l\frac{\mathrm{d}t_a}{\mathrm{d}m} = 0. \tag{25}$$

Using (21) in (25) and rearranging terms, we arrive at (16) concluding the proof. Moreover,

[2] Using typical values of variance for the relative clock skew, the propagation delay and the relative offset - taken from (CHEN et al., 2014) - and $T_s = 100$ seconds in (15) we obtain an approximate 0.001% difference in σ_e values when disregarding σ_τ and σ_θ. This difference will decrease with an increase in T_s. Therefore we consider the approximation tight for large values of T_s

note that in practice instead of $m^\star$ we use the closest integer solution, denoted by $M^\star$. □

3.2.1 UPPER BOUND

Theorem 2. *The optimal amount of synchronization rounds within each maximum synchronization interval T_s is upper bounded by*

$$m_b = \sqrt[3]{\frac{4p^2P_lKT_s\sigma_f}{T_bP_s}} \tag{26}$$

where $m_b \in \mathbb{R}^+$.

Proof. When the total transmit power is much larger than the receive power ($P_r \ll NP_s$), (22) is very well approximated by disregarding the term that considers P_r. This assumption is based on the fact that there are off-the-shelf radios such as the LoRa™ modem (SEMTECH, 2015) which have receive power specifications in the order of 40 mW as opposed to a transmit power of up to 400 mW. This difference is even greater when considering state of the art radio circuitry, whose receive power may be as low as 15 mW (ZHANG et al., 2013). [3] Therefore (20) can be simplified to

$$E(M) \approx M\left(2\sqrt{T_bP_sP_lt_a(M)}\right) + 2pP_lt_a(M). \tag{27}$$

The first step towards minimizing (27) is to replace the integer M with the real m. Then, we determine the convexity constraints for $E(m)$ by evaluating $\frac{\mathrm{d}^2E(m)}{\mathrm{d}m^2} > 0$, which results in (24), and thus we are able to minimize $E(m)$ by solving

$$2\sqrt{T_bP_sP_l}\left(\sqrt{t_a} + \frac{m\frac{dt_a}{dm}}{2\sqrt{t_a}}\right) + 2pP_l\frac{dt_a}{dm} = 0. \tag{28}$$

Using (21) in (28) and rearranging the terms, we arrive at (26). Since the synchronization cost is being reduced by disregarding P_r, the tradeoff tends towards a more synchronized scenario which translates into more frequent synchronizations being optimal, making m_b an upper bound to $m^\star$. □

The upper bound in Theorem 2 can be exploited for obtaining useful insights. Analysing (26) we can see that the optimal number of synchronizations within T_s increases with the frequency that the node has to idly listen for alarms. Also, we note that $m^\star$ decreases with the increase of transmit power, which is intuitive to assume since each synchronization would be

[3] Conversely, many modern radios, as well as some operating modes of the LoRa™ modem (SEMTECH, 2015) do not sustain this condition. In those cases the resulting m_b will still be an upper bound to the curve, but not as tight.

more expensive in terms of energy. Conversely, as P_l grows, $m^\star$ becomes larger, since the node draws more energy for idly listen to the medium and thus a smaller t_g is desirable, which in turn means that synchronizing more often would be less energy consuming. In addition, as shown in (21), the listening window $t_g = 2t_a$ depends directly on $KT_s\sigma_f$, and thus an increase in the value of any of the factors also increases $m^\star$.

Finally, let us recall that we relaxed the optimization solution in order to consider that $\{m^\star, m_b\} \in \mathbb{R}^+$. In practice we assume the closest integer solution of $m^\star$, denoted by $M^\star$.

4 NUMERICAL RESULTS

In this chapter, the results developed in Chapter 3 will be simulated numerically using real world values in order to demonstrate their correctness, the impact of system parameters and potential energy gains of using the proposed scheme.

4.1 SIMULATION RESULTS

Table 1: Simulation Parameters (NADAS et al., 2016)

Beacon duration (T_b)	2 ms (CHEN et al., 2014)
Estimated deviation of clock drift rate (σ_f)	50 ppm (CHEN et al., 2014)
Estimated deviation of clock offset (σ_θ)	20 μ s (CHEN et al., 2014)
Estimated deviation of message delivery delay (σ_τ)	11 μ s (CHEN et al., 2014)
Power consumption for data transmission (P_s)	396 mW (SEMTECH, 2015)
Power consumption for data receiving (P_r)	37 mW (SEMTECH, 2015)
Power consumption for idle listening (P_l)	37 mW (SEMTECH, 2015)
Synchronization confidence level (β_0)	99.5% (CHEN et al., 2014)

In order to investigate the correctness and the impact of the proposed optimization, this section presents some numerical examples using the parameters in Table 1, which are obtained from (CHEN et al., 2014) and (SEMTECH, 2015). First, Figure 4 plots $m^\star$ and m_b, as well as computer simulations[1], as a function of T_s for the case of $p = 4$. It is clear that $m^\star$ grows with T_s, as predicted in Section 3.2. In addition, note that Theorem 1 and the computer simulations agree very well, while the upper bound is just a bit pessimistic. Note that the T_s range used in all the simulations is suitable for applications with σ_e of around 100ms, which is more severe than the Vossoroca example, wherein σ_e = 30s.

[1]The simulations were done by computing the total energy consumption for different values of M using (13) and (14) and comparing the results to obtain $M^\star$.

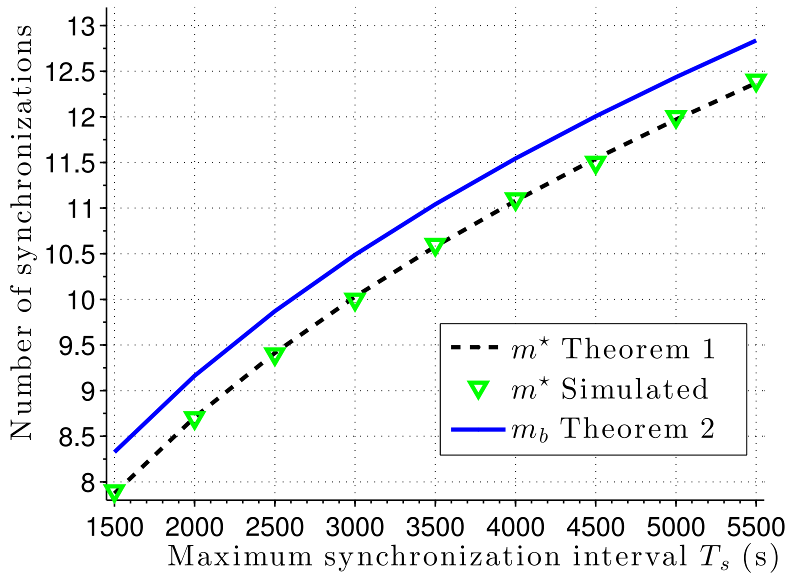

Figure 4: Theoretical and simulated optimal number of synchronizations $m^\star$ within T_s, and the upper bound m_b. (NADAS et al., 2016)

4.2 PARAMETER DEPENDENCE ANALYSIS

As a second form of validating the analytical results, some predictions of Theorem 2 are validated through parameter variation. Changes in T_s, P_l, T_b and P_s are presented in Figures 5 and 6, in order to show that an increase in T_s or P_l impacts in the growth of $M^\star$ whereas an increase in T_b or P_s decreases the $M^\star$, as predicted by the theorem. This results can be used when choosing system parameters, for instance, let us consider certain application wherein due to MAC constraints the maximum value of M is 6, $T_b = 4ms$ and $T_s = 3000s$. Analyzing Figures 5 and 6 we can perceive that in order for $M^\star$ to be possible, the system would have to be designed with both $P_l < 50mW$ and $P_s > 300mW$.

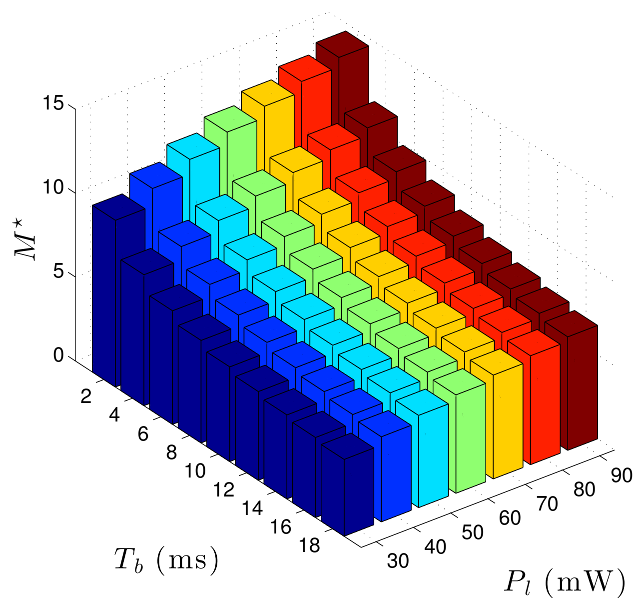

Figure 5: $M^{\star}$ **for different values of** P_l **and** T_b **using** $T_s = 3600\text{s}$

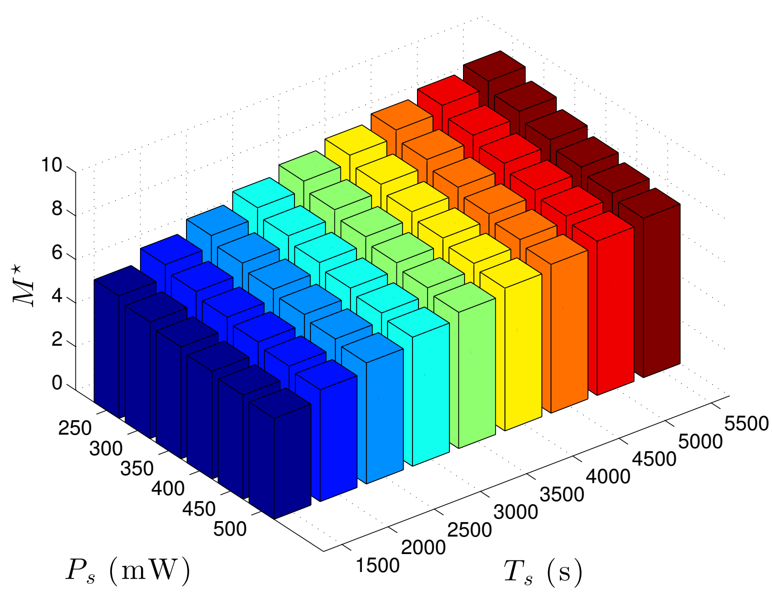

Figure 6: $M^{\star}$ **for different values of** P_s **and** T_s

4.3 COMPARISON WITH THE USUAL APPROACH

We computed the ratio $\eta = \frac{E(M^{\star})}{E(1)}$, between the energy spent when using $M = M^{\star}$ and $M = 1$, in order to show the potential energy savings, when compared to the usual approach (where $M = 1$). Note that, from now on, we only plot the closest integer solution of $m^{\star}$, denoted by $M^{\star}$. Figure 7 plots η for different values of T_s and p, from which we can observe relevant energy savings. For instance, for $p = 6$ and $T_s = 1$ hour the energy consumption is around five times smaller when $M^{\star}$ is employed, while the savings increase with both p and T_s. Moreover, Figure 9 shows the overall energy consumption as a function of M. Note that, as expected, there is an optimal $M^{\star}$ for each set of parameters, while the potential energy savings can be quite large. In addition, Figures 7 and 9 also reveal that the proposed optimization leads to higher energy savings when either p or T_s increase, *i.e.*, applications with severe alarm timing restrictions or low duty-cycles, respectively. Figure 8 shows the same ration as Figure 7 computed for different values of P_s, P_l and P_r (52mW, 59mW and 59 mW respectively), obtained from the XBee-PRO® 900 HP (DIGI, 2015). As it can be seen, even tough the sending and receiving powers are almost identical in this case, the gains are similar.

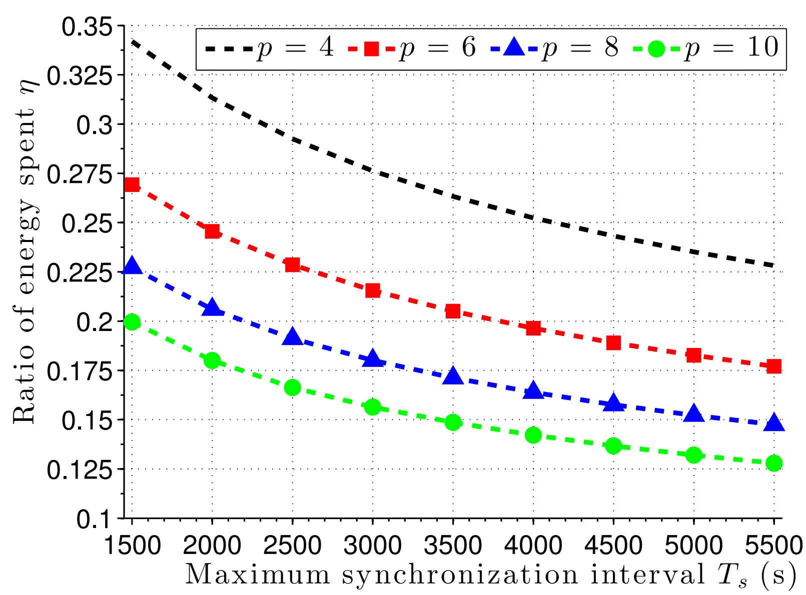

Figure 7: Ratio $\eta = \frac{E(M^{\star})}{E(1)}$ for different values of p and T_s (NADAS et al., 2016), using power consumptions from the LoRa™module (SEMTECH, 2015).

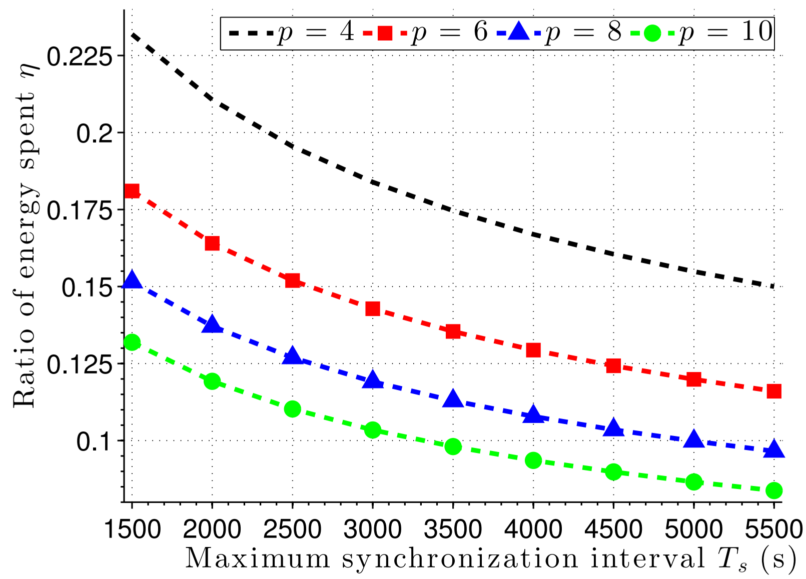

Figure 8: Ratio $\eta = \frac{E(M^{\star})}{E(1)}$ for different values of p and T_s using power consumptions from the XBee-PRO® 900HP (DIGI, 2015).

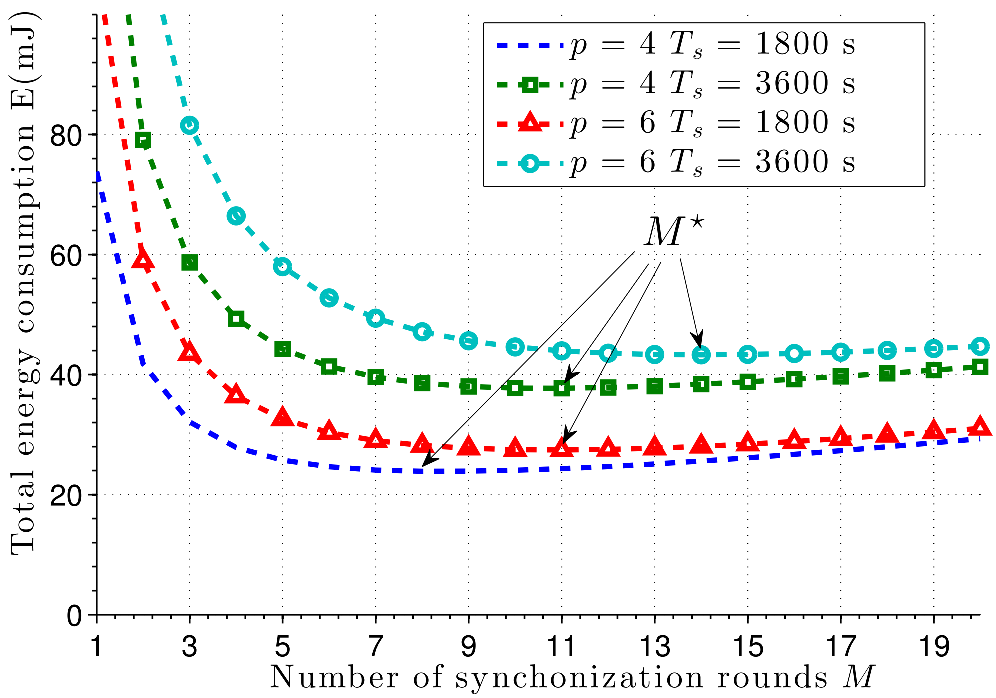

Figure 9: Overall energy consumption as a function of M, for different values of p and T_s. (NADAS et al., 2016)

5 CONCLUSION

In this work we presented a strategy to determine the most energy efficient synchronization frequency in a WSN, while assuming that the wireless nodes must have to idly listen to the medium several times within a maximum synchronization interval as specified by the particular application. This is well justified by a wide range of applications in diverse areas, as discussed in Section 1.2. Moreover, with the proposed optimization we are able to considerably decrease the overall energy consumption required to maintain adequate synchronization. For instance, savings as large as five times were achieved in the numerical results. Keeping in mind that energy is in most cases a crucial factor for WSNs, this result can benefit applications greatly by increasing network lifetime.

In addition, we presented an analytical derivation of the optimal number of synchronizations within a cycle for the operation of a WSN deployed in a scenario with the aforementioned characteristics. Also, an upper bound has been found that allowed us to obtain important insights on the behavior of the proposed optimization for different system parameters. This bound could also be used for adapting the protocol in a scenario with feedback, as it is of far less computational complexity than the exact numerical solution, further increasing the efficiency of the system.

5.1 POSSIBLE EXTENSIONS

This work could be extended in many directions, mainly evolving it towards a more accurate representation of real world applications. Some of these extensions are enumerated below:

1. Considering the effect of the wireless channel on the communication, by accounting for the outage probability on the synchronization rounds, as well as on the alarm detection. In order to do so, the work in (CHEN et al., 2014) has to be revisited accounting for the possibility of outages. A new system model would have to be computed and optimization would have to be performed again.

2. Implementing the proposed idea in practice to measure with real world values the energy impact of applying the proposed technique in order to check if the model contains all significant factors.

3. Accounting for a multi-node scenario. In this extension, the system model would have to be reworked by choosing a protocol for synchronization in multi-node WSN. This could be coupled with the first extension proposed to take into account cooperative communications as well and analysing the impact of it on energy efficiency.

4. Considering the effect of various MAC protocols on the proposed scheme.

REFERENCES

AKYILDIZ, I. F. et al. A survey on sensor networks. **IEEE communications magazine**, IEEE, v. 40, n. 8, p. 102–114, 2002.

AKYILDIZ, I. F. et al. Wireless sensor networks: a survey. **Computer networks**, Elsevier, v. 38, n. 4, p. 393–422, 2002.

AL-KARAKI, J. N.; UL-MUSTAFA, R.; KAMAL, A. E. Data aggregation in wireless sensor networks-exact and approximate algorithms. In: IEEE. **High Performance Switching and Routing, 2004. HPSR. 2004 Workshop on**. [S.l.], 2004. p. 241–245.

ANASTASI, G. et al. Energy conservation in wireless sensor networks: A survey. **Ad hoc networks**, Elsevier, v. 7, n. 3, p. 537–568, 2009.

AUER, G. et al. How much energy is needed to run a wireless network? **IEEE Wireless Communications**, IEEE, v. 18, n. 5, p. 40–49, 2011.

BRAGA, S. M. **Uma nova abordagem para integração entre quantidade e qualidade da água para a avaliação da poluição difusa**. Tese (Doutorado) — Universidade Federal do Paraná , 2013.

BRANTE, G. G. d. O.; KAKITANI, M. T.; SOUZA, R. D. Energy efficiency analysis of some cooperative and non-cooperative transmission schemes in wireless sensor networks. **IEEE Transactions on Communications**, IEEE, v. 59, n. 10, p. 2671–2677, 2011.

CHEN, Y.; QIN, F.; YI, W. Guard beacon: An energy-efficient beacon strategy for time synchronization in wireless sensor networks. **IEEE Communications Letters**, IEEE, v. 18, n. 6, p. 987–990, 2014.

DEMIRKOL, I.; ERSOY, C.; ONUR, E. Wake-up receivers for wireless sensor networks: benefits and challenges. **IEEE Wireless Communications**, IEEE, v. 16, n. 4, p. 88–96, 2009.

DIGI. **XBee-PRO® 900HP**. [S.l.], 2015.

DONNO, D. D.; CATARINUCCI, L.; TARRICONE, L. Ultralong-range rfid-based wake-up radios for wireless sensor networks. **IEEE Sensors Journal**, IEEE, v. 14, n. 11, p. 4016–4017, 2014.

ELSON, J.; GIROD, L.; ESTRIN, D. Fine-grained network time synchronization using reference broadcasts. **ACM SIGOPS Operating Systems Review**, ACM, v. 36, n. SI, p. 147–163, 2002.

GANERIWAL, S. et al. Estimating clock uncertainty for efficient duty-cycling in sensor networks. **IEEE/ACM Transactions on Networking (TON)**, IEEE Press, v. 17, n. 3, p. 843–856, 2009.

GOLDSMITH, A. J.; WICKER, S. B. Design challenges for energy-constrained ad hoc wireless networks. **IEEE wireless communications**, IEEE, v. 9, n. 4, p. 8–27, 2002.

GREUNEN, J. V.; RABAEY, J. Lightweight time synchronization for sensor networks. In: ACM. **Proceedings of the 2nd ACM international conference on Wireless sensor networks and applications**. [S.l.], 2003. p. 11–19.

GRILO, A.; MACEDO, M.; NUNES, M. An energy-efficient low-latency multi-sink mac protocol for alarm-driven wireless sensor networks. In: **Wireless Systems and Mobility in Next Generation Internet**. [S.l.]: Springer, 2007. p. 87–101.

GUTIÉRREZ, J. et al. Automated irrigation system using a wireless sensor network and gprs module. **IEEE transactions on instrumentation and measurement**, IEEE, v. 63, n. 1, p. 166–176, 2014.

HOBLOS, G.; STAROSWIECKI, M.; AITOUCHE, A. Optimal design of fault tolerant sensor networks. In: IEEE. **Control Applications, 2000. Proceedings of the 2000 IEEE International Conference on**. [S.l.], 2000. p. 467–472.

HOFFMAN, B.; LICHTENEGGER, H.; COLLINS, J. **GPS–Theory and Practice**. [S.l.]: Springer-Verlag: New York, USA, 1997.

LANEMAN, J. N. Cooperative communications in mobile ad hoc networks. **IEEE Signal Processing Magazine**, v. 1053, n. 5888/06, 2006.

LEE, H.-C. et al. Design of a multifunctional wireless sensor for in-situ monitoring of debris flows. **IEEE Transactions on Instrumentation and Measurement**, IEEE, v. 59, n. 11, p. 2958–2967, 2010.

LEE, H.-C. et al. The tube: A rapidly deployable wireless sensor platform for supervising pollution of emergency work. **IEEE Transactions on Instrumentation and Measurement**, IEEE, v. 61, n. 10, p. 2776–2786, 2012.

LEE, K. Y.; EL-SHARKAWI, M. A. **Modern heuristic optimization techniques: theory and applications to power systems**. [S.l.]: John Wiley & Sons, 2008.

LI, Q.; RUS, D. Global clock synchronization in sensor networks. **IEEE Transactions on computers**, IEEE, v. 55, n. 2, p. 214–226, 2006.

MARCELLONI, F.; VECCHIO, M. A simple algorithm for data compression in wireless sensor networks. **Communications Letters**, IEEE, v. 12, n. 6, p. 411–413, 2008.

MARÓTI, M. et al. The flooding time synchronization protocol. In: ACM. **Proceedings of the 2nd international conference on Embedded networked sensor systems**. [S.l.], 2004. p. 39–49.

MEULEN, E. C. V. D. Three-terminal communication channels. **Advances in applied Probability**, JSTOR, p. 120–154, 1971.

MILLS, D. Network time protocol (version 3) specification, implementation and analysis. 1992.

MORITZ, G. L. et al. Time-switching uplink network-coded cooperative communication with downlink energy transfer. **Transactions on Signal Processing**, IEEE, v. 62, n. 19, p. 5009–5019, 2014.

NADAS, J. P. B. et al. Rede sem fio de sensores aplicada no monitoramento inteligente de reservatórios. In: **XXI Simposio brasileiro de recursos hidricos**. [S.l.: s.n.], 2015.

NADAS, J. P. B. et al. Energy efficient beacon based synchronization for alarm driven wireless sensor networks. **IEEE Signal Processing Letters**, IEEE, v. 23, n. 3, p. 336–340, 2016.

NOVOTNY, V. **Water quality: Diffuse pollution and watershed management**. [S.l.]: John Wiley & Sons, 2003.

PANTAZIS, N. A.; NIKOLIDAKIS, S. A.; VERGADOS, D. D. Energy-efficient routing protocols in wireless sensor networks: A survey. **Communications Surveys & Tutorials**, IEEE, v. 15, n. 2, p. 551–591, 2013.

PIONKE, H. B.; GBUREK, W. J.; SHARPLEY, A. N. Critical source area controls on water quality in an agricultural watershed located in the chesapeake basin. **Ecological Engineering**, Elsevier, v. 14, n. 4, p. 325–335, 2000.

RAULT, T.; BOUABDALLAH, A.; CHALLAL, Y. Energy efficiency in wireless sensor networks: A top-down survey. **Computer Networks**, Elsevier, v. 67, p. 104–122, 2014.

ROSAS, F. et al. Optimizing the code rate of energy-constrained wireless communications with harq. **IEEE Transactions on Wireless Communications**, IEEE, v. 15, n. 1, p. 191–205, 2016.

SEMTECH. **SX1272/73 - 860 MHz to 1020 MHz Low Power Long Range Transceiver**. [S.l.], 3 2015.

SHAQADAN, A. A.; AL-RAWASHDEH, M. Quantification of hydrologic variability impact on nps pollution of ungaged catchments. In: **International Conference Recent treads in Engineering I& Technology**. [S.l.: s.n.], 2014. p. 47–50.

SICHITIU, M. L.; VEERARITTIPHAN, C. Simple, accurate time synchronization for wireless sensor networks. In: IEEE. **Wireless Communications and Networking, 2003. WCNC 2003. 2003 IEEE**. [S.l.], 2003. v. 2, p. 1266–1273.

URTEAGA, I.; BARNHART, K.; HAN, Q. Redflag: A run-time, distributed, flexible, lightweight, and generic fault detection service for data-driven wireless sensor applications. **Pervasive and Mobile Computing**, Elsevier, v. 5, n. 5, p. 432–446, 2009.

WETZEL, R. G. **Limnology: lake and river ecosystems**. [S.l.]: Gulf Professional Publishing, 2001.

WOOD, A. et al. Alarm-net: Wireless sensor networks for assisted-living and residential monitoring. **University of Virginia Computer Science Department Technical Report**, v. 2, 2006.

WU, Y.-C.; CHAUDHARI, Q.; SERPEDIN, E. Clock synchronization of wireless sensor networks. **IEEE Signal Processing Magazine**, IEEE, v. 28, n. 1, p. 124–138, 2011.

YE, W.; SILVA, F.; HEIDEMANN, J. Ultra-low duty cycle mac with scheduled channel polling. In: ACM. **Proceedings of the 4th international conference on Embedded networked sensor systems**. [S.l.], 2006. p. 321–334.

ZHANG, L. et al. A reconfigurable sliding-if transceiver for 400 mhz/2.4 ghz ieee 802.15. 6/zigbee wban hubs with only 21% tuning range vco. **IEEE Journal of Solid-State Circuits**, IEEE, v. 48, n. 11, p. 2705–2716, 2013.

ZHAO, X. et al. An efficient broadcast authentication protocol in wireless sensor networks. **Chinese Journal of Electronics**, v. 18, n. 2, p. 368–372, 2009.