Robustness in Low Power Wide Area Networks

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Abstract

During the past few years we have witnessed an emergence of Wide Area Networks in the Internet of Things area. There are several new technologies like LoRa, Wi-SUN, Sigfox, that offer long range communication and low power for low-bitrate applications. These new technologies enable new application scenarios, such as smart cities, smart agriculture, and many more. However, when these networks co-exist in the same frequency band, they may cause problems to each other since they are heterogeneous and independent. Therefore it is very likely to have frame collisions between the different networks.

In this thesis we first explore how tolerant these networks are to Cross Technology Interference (CTI). CTI can be described as the interference from heterogeneous wireless technologies that share the same frequency band and is able to affect the robustness and reliability of the network. In particular, we select two of them, LoRa and Wi-SUN and carry out a series of experiments with real hardware using several configurations. In this way, we quantify the tolerance of cross technology interference of each network against the other as well as which configuration settings are important.

The next thing we explored is how well channel sensing mechanisms can detect the other network technologies and how they can be improved. For exploring these aspects, we used the default Clear Channel Assessment (CCA) mechanism of Wi-SUN against LoRa interference and we evaluated how accurate it is. We also improved this mechanism in order to have higher accuracy detection against LoRa interference.

Finally, we propose an architecture for WSNs which will enable flexible re-configuration of the nodes. The idea is based on Software Defined Network (SDN) principles and could help on our case by re-configuring a node in order to mitigate the cross-technology interference from other networks.
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Included Papers

This thesis is based on the following papers

I Charalampos Orfanidis, Laura Marie Feeney, Martin Jacobsson, Per Gunningberg. *Investigating interference between LoRa and IEEE 802.15.4g networks*. IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2017.

II Charalampos Orfanidis, Laura Marie Feeney, Martin Jacobsson, Per Gunningberg. *Improving LoRa/IEEE 802.15.4g co-existence*. (Submitted), 2018.


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List of work not included in this thesis


**V** Charalampos Orfanidis, Laura Marie Feeney, Martin Jacobsson. *Measuring PHY layer interactions between LoRa and IEEE 802.15.4g networks*. (Poster) IFIP Networking, 2017.
## Contents

I Thesis 3

1 Introduction 5
   1.1 Contributions 6
   1.2 Internet of Things 6
   1.3 Low Power Wide Area Networks 7
   1.4 Cross Technology Interference 7
   1.5 Robustness 8
   1.6 Thesis Outline 8

2 Related Work 9
   2.1 Low Power Wide Area Networks in IoT 9
   2.2 Clear Channel Assessment 10
   2.3 SDN for Sensor Network 11

3 Research Questions and Contributions 13
   3.1 Methodology 13
   3.2 Co-existence in LPWAN 14
      3.2.1 Research question 14
      3.2.2 CTI evaluation 15
   3.3 Improving LPWAN co-existence 17
      3.3.1 Research question 18
      3.3.2 The CCA mechanism 18
   3.4 SDN for IoT 20
      3.4.1 Research question 21
      3.4.2 SDN architecture for tailoring IoT devices 21

4 Summary of Papers 23
   4.1 Paper I: Investigating interference between LoRa and IEEE 802.15.4g networks 23
   4.2 Paper II: Improvement of LoRa/IEEE 802.15.4g co-existence 23
4.3 Paper III: Using Software-defined Networking Principles for Wireless Sensor Networks

5 Conclusion

II Papers

Paper I - Investigating interference between LoRa and IEEE 802.15.4g networks

Paper II - Improvement of LoRa/IEEE 802.15.4g co-existence

Paper III - Using Software-defined Networking Principles for Wireless Sensor Networks
Part I

Thesis
Chapter 1

Introduction

The arriving of Low Power Wide Area Networks (LPWAN) technologies brings new features and properties to the Internet of Things (IoT) domain, such as long range communication and robustness in combination with low power consumption and low bitrate. These new features enrich the use case list with application scenarios like smart cities, smart agriculture, building management, and many more. As a consequence, the amount of these networks are increasing and thus the possibility of Cross Technology Interference (CTI) between these various networks will be higher which will affect the performance of the networks.

In this thesis, we investigate the CTI effect between two LPWAN technologies (LoRa and Wi-SUN) when they are deployed in the same environment. Most of the LPWANs are using the unlicensed spectrum because it is free and does not require any administration procedure to use it. Thus, wireless networks in unlicensed spectrum are increasing in popularity and it is very likely to have co-existing issues between LPWANs in the near future. In the next paragraph we describe from a high level position our approach to deal with the issues.

We selected two emerging network technologies, LoRa [1] and Wi-SUN [2], and we quantified the tolerance degree of each during the presence of the other. After achieving insights to this problem, we evaluated the existing collision avoidance mechanisms against these technologies and proposed improvements in order to increase the detection accuracy and have less frame collisions. Finally, we proposed a WSN architecture, which will allow flexible node re-configuration. Using this architecture, a network would be more easier to be adjusted to new requirements, such as mitigating CTI more efficiently. We believe that the problems we are trying to tackle, are important in order to have a sustainable co-existence in the IoT ecosystem among existing heterogeneous networks as well as emerging ones.
1.1 Contributions

This thesis is oriented around three papers and their investigated research questions accordingly. To this end, we sum up our contributions as follows:

- The investigation of LoRa and Wi-SUN Technologies co-existing in the same frequency band and coverage space allowed us to quantify the CTI in terms of Packet Received Ratio (PRR\(^1\)) of the two networks to each other and which factors affect CTI. A systematic measurement using highly controlled scenarios that allow us to collect a large amount of results that gave confidence to support our arguments and conclusions.

- We evaluated on real hardware how accurate the Clear Channel Assessment (CCA) mechanism of Wi-SUN is able to detect LoRa transmissions. Moreover we proposed an improved version of the Wi-SUN CCA which is more accurate and more energy efficient.

- In the theme of Software Defined Networking (SDN), we propose an architecture for resource constrained sensor networks that can be used to offer software re-configuration features in the context of IoT. The contribution here are insights into how and why SDN principles can be applied to sensor networks, what are the challenges, and possible solutions.

In the rest of this chapter, we introduce some fundamentals concepts about IoT, LPWAN, CTI and robustness.

1.2 Internet of Things

The IoT vision can be described as follows: physical devices, such as vehicles, healthcare products, industry tools, machines, and many more are interconnected in order to collect data through sensors. Furthermore some of these devices can act based upon the collected data or transmit these data through communication protocols. IoT is enabling a new way to interact with the physical environment. One of the early motivations for envision IoT comes from the fact that the Internet data was generated mostly from humans (text, photos, videos, etc). Therefore, in order to have more information online and increase the accuracy of it, we need a system that includes objects that will have the role of collecting data from the physical world and making them available online.

\(^{1}\)The ratio of received to sent packets
IoT has evolved into one of the most attractive fields of computer science and industry as well. There are so many application scenarios where IoT is applied, including smart cities, healthcare, smart agriculture, retail, environmental monitoring, and many more.

Today, IoT in computer science is a huge field (including different topics). The one we will focus in this thesis is the co-existence of Wide Area Networks in IoT.

1.3 Low Power Wide Area Networks

The LPWAN can be described as a low power wireless network technology that was designed for communication over longer range for low bit rate devices. The long range communication is enriching the application scenario list with new use cases that would not be able to be realized with current technologies so far or it would be very expensive, especially from an energy point of view. LPWAN one of the main components of the IoT ecosystem which is enabling long range communication.

The advances in LPWAN have resulted in new protocols and standards such as LoRa [1], Sigfox [3], IEEE 802.15.4g Wi-SUN [4], NB-IoT [5] and many more. However, integrating LPWAN in the IoT ecosystem includes challenges that we have to overcome in order to have a proper co-existence between different LPWAN technologies that are already there or will arrive in the future.

1.4 Cross Technology Interference

Using the unlicensed spectrum is attractive because everyone can deploy a wireless network and avoid a complex and costly administration overhead associated with reserved spectrum. In the environment of unlicensed spectrum, the domain of the Industrial Scientific Medical (ISM) bands, where one does not need a license to deploy a wireless device, there are many wireless technologies that have to co-exist within the same transmission range. When these networks co-exist, it is very common that their performance will be degraded due to frame collisions [6]. In this thesis, we focus on the impact of the Cross Technology Interference (CTI) that occurs at the 868 MHz by taking into consideration co-existing communication from LPWAN devices. The impact of CTI in this domain differs from traditional sensor network communications due to different characteristics of the new networks. The main characteristics that are different are the low bitrate and long range communication.
1.5 Robustness

Robustness in computer systems can be defined as the property of a system which is stable and performs as expected and designed even when the conditions (i.e. environmental) are not the ones which the system was designed for. Robustness should not be confused with reliability as it is a different property. The probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment [7]. On the contrary, robustness ensures that a system will perform as intended even when these conditions vary to a certain threshold. For instance, a robust radio platform will be able to transmit and receive messages even when environmental conditions such as temperature or humidity deviates from the ones it was designed for.

In order to have a robust system, the system itself must be tested under different variations of conditions that might harm the performance. The system should be designed in such a way that it tolerates a specified level of varied conditions, possibly with some performance degradation.

In this thesis we investigate how robust LPWANs are under a certain degree of CTI and how we can increase the robustness.

1.6 Thesis Outline

This thesis is organized as follows: Chapter 2 presents the state of art and research that are related on the presented problems. Next in Chapter 3, we raise the research questions again and we lay out parts of our contributions and results. Chapter 4 summarizes the research papers on which this thesis is based on. Chapter 5 concludes the thesis. Part II of the thesis presents full versions of the included papers. The papers have all technical details and results that can not be commented in the main body of this thesis.
Chapter 2

Related Work

This chapter presents the related work to this thesis focusing on three main sections: LPWANs in IoT, Clear Channel Assessment (CCA) mechanisms in IoT and Software Defined Networking (SDN) for sensor network.

2.1 Low Power Wide Area Networks in IoT

Many LPWAN technologies such as LoRa [1], Sigfox [3], IEEE 802.15.4g Wi-SUN [4], NB-IoT [5], are emerging at the moment. LoRa is one of them and is getting attention both from industry and academia due to its use of unlicensed spectrum and due to the long range and robust performance. The current scientific literature is mostly focusing on investigating the transmission range, capacity and scalability. In [8, 9, 10], the authors are examining the performance of LoRa in several settings and conditions. Bor et al. in [8], propose a mechanism for setting optimized parameters in regard to requirements set by the user on the link quality and the energy consumption. Different environments and vegetation specifically may affect LoRa performance according to [10].

LoRa scalability is studied in [11, 12, 13]. Georgiou et al. in [11] look into the coverage of a LoRa network with a single gateway. The results show that increasing the number of end-devices decreases the effective coverage exponentially due to the interference from multiple nodes. Using simulations, the authors in [12] show that using multiple base stations improves the network performance even under the occurrence of interference.

A paper which is related to the main contribution of this thesis is [14]. Here, the authors conduct an empirical investigation of interference between LoRa networks. The authors are looking into the case where there are two interfering LoRa radios when one is using 2-GFSK modulation and the other the default Chirp Spread Spectrum (CSS). Unfortunately, the results vary a
lot between them and it is difficult to draw solid conclusions regarding the behaviour of interference.

2.2 Clear Channel Assessment

Clear Channel Assessment (CCA) is a common method used in IEEE 802.15.4 [15] in order to detect if someone is using the radio channel and refrain to send until is is free. Consequently this is used to countermeasure interference and frame collisions. The node who wants to use the channel is sampling the medium by getting Received Signal Strength Indicator (RSSI) values. An RSSI value can be used to characterise how strong a frame is or characterize the background noise. If this value is above a threshold, the node does not proceed with transmitting but instead it is entering a back-off algorithm that decides how long it will wait until it will measure the signal strength again. However, this is a traditional mechanism and the research community has proposed many improvements. For instance, Sparber et al. [16], presents Dynamic CCA. This approach dynamically modifies the threshold in CCA for the Tmote sky platform. It increases the Packet Received Ratio (PRR), which can be described as the ratio between the received and transmitted frames, and decreases the consumed energy of the network. In duty cycle approaches, the node turns its radio off in order to consume less energy. This is known as sleep state. Accordingly, it turn its radio on again to send or receive a frame, this a wake up state. A similar approach, which also sets a threshold is [17], where the threshold level is adjusted based on application specific requirements in order to reduce the false wake ups from the radio. Their results illustrate that in the presence of interference, the length of the duty cycle is increased, which is desirable from energy point, while still the links remain equally reliable.

CCA is also studied in the presence of CTI. Yuan et al. in [18], presents a CCA mechanism designed for IEEE 802.15.4 where the threshold is adjusted regarding the type of interference, focusing on a scenario where the network co-exists with a IEEE 802.11 network. So when the interference is increased a lot, the threshold changes accordingly. However the IEEE 802.11 network uses much more powerful transmissions so that the results may not be applicable directly on LPWANs. Simulation results shows that the throughput can be increased without increasing the energy consumption of the network. Another project modifying CCA when IEEE 802.15.4 and IEEE 802.11 co-exists is described in [19]. The proposed modification here is trying to identify the source of interference and adjust the operation of CCA accordingly. The throughput is improved by 35% in moderate interference environments according the presented results.
2.3 SDN for Sensor Network

SDN is an idea developed to increase the flexibility of the regular wired computer networks. The basic principal here is the decoupling between the control plane and the data plane, as it is implemented in OpenFlow[20] the most popular SDN approach. Replacing the control plane functionality enables network control and management from a higher layer something which decreases complexity. However, applying these principles in embedded network devices like sensor networks or LPWANs include several challenges. SDN principles in sensor networks has been studied in [21], where OpenFlow is deployed in a sensor network. However, the paper presents limited set of results that are hard to draw general conclusions from. A similar attempt is carried out in [22] with a SDN-based sensor networks. Here, forwarding tables and in-network aggregation of sensed data are configurable. This brings flexibility to the network. Finally the authors propose a mechanism for gathering topology data to communicate with the controller and from the controller to represent the current topology.

It is well known that in sensor networks, the MAC protocols need to be application oriented. This means that depending on the application scenario, the performance of the MAC protocol may focus on different aspects such as energy consumption, throughput, etc. Thus, researchers have proposed MAC protocols that have the ability to be re-configured or adapt to new settings. T-MAC [23] is one of the early approaches where the listening period is adaptive. C-MAC [24] is a more recent approach which is enabling reconfiguration of many parameters of the MAC by the application. In pTunes [25], the MAC protocol parameters are optimized with a proposed model. Network data are collected in a base station where the model optimizes the configuration of the MAC protocol. In snapMac [26], the radio layer can programmed with a sequence of simple commands called a chain. The whole approach is like using a Virtual Machine (VM) with a small dynamic set of low-level instructions.

The authors of [27] propose IMPERIA, which is a centralized architecture for sensor networks where a user is able to determine MAC, routing, and management mechanisms. The scope here is to move the functionality to a central entity, like in SDN.
Chapter 3

Research Questions and Contributions

In this chapter, we describe the research questions which lead to the contributions of this thesis. First we answer on how much the two radios, LoRa and Wi-SUN tolerate each other when they co-exist. Then we give an answer on how accurate is Wi-SUN default CCA against LoRa transmissions and how it can be improved. Finally we answer on if we can use SDN principles in order to implement an architecture for sensor networks which will offer re-configuration features?

3.1 Methodology

We articulated hypotheses by analysing the research problems and studied the latest scientific literature thoroughly. The methodology we used is mostly based on experiments on real hardware trying to represent real life scenarios, repeated under different configurations in order to capture a large domain of conditions. This required us to conduct systematic analyses of the problems and thereby answer the research questions we raised. The plethora of results we obtained allowed us to draw conclusions and discuss future steps of our work.

First we investigated how two popular LPWAN platforms, LoRa and IEEE 802.15.4g Wi-SUN, are affecting each other when they are deployed in the same environment. For that we deployed the hardware in an anechoic chamber in order to eliminate any external noise and have a highly control environment. After completing the experiments we analysed the results to reach on conclusions. In the next part of our research, we used a RF combiner and signal attenuators again to have a controlled environment. This was used to evaluate and improve the CCA mechanism when it is operating under
LoRa transmissions in order to be more accurate and more energy-efficient. Again after obtaining the results we analysed them to draw conclusions on them. Finally, we proposed a SDN-based architecture for reconfigurable sensor networks which enables the use of commodity hardware in tailored manner following the application requirements. This part did not include implementation and experimental part.

3.2 Co-existence in LPWAN

Smart city and smart building IoT applications will require stable operation in environments where interference from different sources occurs. These application scenarios comprise several offered services including healthcare where availability and robustness requirements are of high importance. Thus, we need to make sure that in an environment with several interfering networks and noise, services with high demanding robustness and availability requirements will be able to operate properly.

LPWANs are getting popular because they are offering features that enable new application scenarios in IoT. Therefore it is expected to see more and more of these networks. Most of the LPWANs are operating in the unlicensed spectrum. As a result, the number of networks using it is increasing and the possibility of having several networks deployed in the same environment using the same frequency, increases as well. We have to mention that these networks are heterogeneous in terms of radios, communication protocols, data rate, communication range, etc. As a result we might have overcrowded areas, where network co-ordination is not trivial because of the heterogeneity and consequently high levels of CTI.

To this end, we need to understand the impact of CTI in LPWANs. Ensuring that applications including LPWANs, will operate reliably and robustly is an important step that we need to establish.

3.2.1 Research question

The research question we address first is how much the two radios (LoRa and Wi-SUN) tolerate each other when they are deployed in the same environment. A follow up question is which factors (e.g. configuration settings in LoRa) may affect this phenomenon. The importance of the results comes from the fact that they give insights in both radio platforms, which might be useful for designing collision avoidance mechanisms and offer robustness to the higher layers.
3.2.2 CTI evaluation

During the CTI evaluation between LoRa and Wi-SUN, we conducted experiments with real hardware and investigated a main scenario with three nodes. The purpose of the evaluation was to collect several data under different configuration settings in order to answer the stated research question. In the first configuration we used two Wi-SUN nodes, a receiver and a transmitter, and we were sending frames as fast as possible. At the same time we used a LoRa node to send frames almost continuously to act as an interferer. In the second configuration, we repeated the same scenario but we inverted the roles and this time we had two LoRa nodes communicating and one Wi-SUN acting as interferer. In this way we examined both how LoRa affects Wi-SUN and how Wi-SUN affects Lora. During the experiments we were altering several setting parameters of LoRa and Wi-SUN in order to quantify the effect of CTI between the two networks and identify how different configurations affect CTI.

The results from the LoRa interference measurements are presented in the form of heatmaps, illustrated in Figure 3.1. The different set of blocks in Figure 3.1 represent different configurations parameters of LoRa, namely Spreading Factor (SF) and Bandwidth (BW). Figure 3.1 represents only a part of the explored parameter space, the complete set of results are presented in Paper I. Each block illustrates different transmission power settings of the IEEE 802.15.4g Wi-SUN transmission ranging from 2 to 12 dBm. In LoRa, SF is the ratio between the chip rate and the underlying symbol rate and BW is the distance between the lowest and highest frequency a chirp can go. Within the block, each Packet Received Ratio (PRR) level is represented with a different shade of blue. White color represents 0% PRR and dark blue 100% PRR. The PRR color is given for IEEE 802.15.4g frames received using each of five IEEE 802.15.4g channels, 24 to 28, marked on the x-axis in each block. The LoRa interference transmission power used was from 2 to 10 dBm, noted on the y-axis.

As expected, we observe in the results that the value of bandwidth in LoRa was responsible for how many channels it will interfere in the Wi-SUN communication. The channels in IEEE 802.15.4g standard is 200 kHz wide and we see that when the bandwidth of LoRa is 125 kHz in Figure 3.1a, only channel 26 is affected, but when the bandwidth is changed to 500 kHz in Figure 3.1b, 3 or 4 channels are affected. This happens because the robustness is dependent on the ratio of the transmission power and interference power, but also on the fact that there is a partial overlap on some channels and when the previous ratio (transmission power over interference power) is on their favour, they have better PRR.

Another expected observation we saw is when we increased the Wi-SUN
transmission power, more frames are successfully received. This is illustrated in figure 3.1a, when both LoRa and Wi-SUN is transmitting at 2 dBm, the PRR is 0%, but when the transmission power of Wi-SUN is 12 dBm, the PRR is 74%. LoRa’s uses Chirp Spread Spectrum (CSS) modulation, where the signals are chirps which are changing their frequency continuously to represent information. On the other hand, Wi-SUN uses 2 GFSK modulation which uses two fixed frequency peaks to represent 0s and 1s. When the relative transmission powers are in Wi-SUN’s favour and the frequencies in the two modulations are not overlapping, some Wi-SUN frames are received successfully.

We also noticed that the SF of LoRa modulation is a factor that affects the overlapping degree of the two signals. More specifically, when we increase the SF value, the PRR of the Wi-SUN transmissions slightly decreases. We believe that this is caused by the nature of LoRa’s modulation. When the SF increases, the angle of the chirp becomes less steep and overlaps in a higher degree with the GFSK. Figure 3.2 depicts the angle for two SF values, SF7 and SF8. Wi-SUN is more tolerant to LoRa with a smaller SF value since the two signals overlap less in time.
3.3 Improving LPWAN co-existence

LoRa and Wi-SUN are two platforms which were introduced in the previous section. Wi-SUN uses the IEEE 802.15.4 standard [15], which includes a CSMA based media access control layer and defines a CCA mechanism based on channel sensing. The transmitter checks if the channel is occupied and if that is the case, it uses a random back-off function to avoid another collision. LoRa radios do not use similar mechanisms to sense the channel, but instead is based on duty cycle limitations to achieve co-existence.

The radios operating in the unlicensed spectrum in the domain of IoT are heterogeneous as we mentioned before. Therefore, it can be difficult for a radio to detect another one which uses different channelization or modulation. CCA-based mechanisms may not perform as expected in such cases. Since we know already from [28] that LoRa transmissions are more robust we focus on CCA performance which may be crucial to establish a proper co-existence between LoRa and Wi-SUN.

Figure 3.2: Illustration of how the angle of the chirp changes when we change the SF in LoRa captured from a SDR. Time is along x-axis and frequency in on the y-axis.

LoRa transmissions subject to Wi-SUN interference proved to be very robust and the PRR seems to drop only in scenarios when the relative transmission powers were not in LoRa’s favour or when the interferer was placed very closed to LoRa. This is probably due to the fact that LoRa modulation principles are based on chirp spread spectrum techniques, which is known to offer high robustness. Additional results are presented in Paper I.

(a) SF7 BW500 kHz  
(b) SF8 BW500 kHz
3.3.1 Research question

Typical future IoT ecosystems include several disparate networks operating simultaneously and many times in the same environment. The CCA method is a common mechanism to avoid collisions in this context. The research question here is how accurate is the Wi-SUN CCA mechanism under the interference of LoRa transmissions? Furthermore, how can an improved CCA version, which is more effective against LoRa interference, be designed? The results we present show that with the proposed improvement on this mechanism we can avoid some collisions and use the shared spectrum more efficiently.

3.3.2 The CCA mechanism

The first step of CCA is sensing the channel in order to check if it is busy or not. To this end, we tried to measure how accurate a Wi-SUN radio can sense LoRa transmissions with CCA. In order to do so, we used real hardware instead of using an anechoic chamber to run the experiments, we connected the nodes to a RF combiner with attenuators to regulate the transmitted power. The RF combiner connects the nodes with wires and the attenuators decrease the signal strength. In this way, we simulate a real-life setting, but at the same we eliminate any external noise. The configuration here consists of two nodes, one Wi-SUN and one LoRa and an attenuator of 30 dB. The Wi-SUN node is set to a fixed channel of 200 kHz and samples 400 RSSI values in order to capture the LoRa signals if they occur. In order to cover full, partial, and no overlap in terms of frequencies, LoRa starts transmitting at an offset of -500 kHz from the fixed channel of Wi-SUN and it stops at +500 kHz offset, in steps of 10 kHz. We repeated this experiment for different parameters of LoRa. We have to mention that LoRa is transmitting almost continuously trying to occupy the channel all the time. The results illustrate the mean of the captured RSSI values in Figure 3.3. The gray background represents the channel used by Wi-SUN and the different curves represent how well Wi-SUN is able to sense a LoRa transmission for a given LoRa configuration.

In Figure 3.3, LoRa’s transmission power is 14 dBm and the attenuator is 36 dB, so we expect to see the captured LoRa transmissions mean value close to -22 dBm at 0 kHz offset, but this is not what we observe. This is happening because of chirp spread spectrum modulation used by LoRa. In this modulation, the energy is spread across the used bandwidth. The bandwidth values from LoRa in this experiment is either 125 or 500 kHz and the filter bandwidth from Wi-SUN is 98 kHz. Thus, Wi-SUN cannot capture the whole energy even where the two radios are completely aligned because
3.3. Improving LPWAN co-existence

Figure 3.3: The Wi-SUN nodes ability to sense different configurations of LoRa by sampling the channel energy. The LoRa central frequency is shifted in steps of 10 kHz. Wi-SUN is sampling at a fixed channel at offset 0 kHz and represented by the gray background.

the filter bandwidth from Wi-SUN is smaller and LoRa spreads its energy across its bandwidth which is always larger in this case. This explains why CCA cannot identify LoRa accurately and this is crucial because CCA will base the decision of sending or refrain on a value like this.

Another observation we notice is that even when LoRa is transmitting within the channel that Wi-SUN is sampling, the standard deviation, illustrated by bars in 3.3, is large. This is something that we need to consider because the RSSI value will indicate a LoRa transmission and an imprecise indication may instead lead to a frame collision.

These observations gave us some insights about Wi-SUN CCA under LoRa transmissions and we decided to try to find an improved CCA version tailored for detecting LoRa. The default version of CCA in Wi-SUN is sampling one RSSI value and if it is higher than the defined threshold a back off operation takes place. What we propose is to take multiple subsequent RSSI values instead of one, select the maximum and then compare with a threshold. In order to compare the precisions of the two CCA mechanisms, we conducted the following experiment. A Wi-SUN transmitter sends packets as fast as possible to a receiver and at the same time, we also have a LoRa node continuously sending frames to create interference. Wi-SUN transmitter carries out CCA before transmission and notes down if it detected LoRa or not in the channel, but sends the frame in any case. With this experiment we show the CCA decisions were correct or not since we sent the frames anyway and we see if there was a collision or not. We create a confusion matrix [29] for both mechanisms, including the following metrics: True Positive (TP) is when a collision occurred and the CCA marked the channel as busy, False Positive (FP) is when a collision occurred, but CCA marked the channel as idle. True Negative (TN) is when there was no collision and CCA marked channel as idle and False Negative (FN) is when a collision occurred, but CCA marked the channel as occupied. The results
of the two CCA versions are depicted in Figure 3.4a and 3.4b for a couple of LoRa settings.
Figures 3.4a and 3.4b show how the TP and FP are improved. The extended CCA sampling period is explaining why the proposed design is detecting the LoRa signals more accurately. However, we have to mention that the default version of CCA has better TN and FN values. We believe that the selection of maximum RSSI value is preventing cases that a successful transmission could have been achieved.

3.4 SDN for IoT

Currently, there is a trend that physical objects that we use in our everyday life acquire connectivity/actuation/sampling abilities and become smart. This is one important step to the realization of IoT vision. Sensor networks can provide local or short range communication in smart objects with low power consumption.

Wireless Sensor Network (WSN) is a field in computer science that has been investigated thoroughly the last decades. There are numerous application scenarios and many environments which can be deployed including residential areas, industrial environments, outdoor urban/rural areas, etc. The application scenarios are heterogeneous because the requirements differ a lot between them. For instance, a real time application with hard delay requirements for monitoring a nuclear plant is very different from an application monitoring temperature and moisture levels in a smart home for indoor climate control.

One important aspect in order to realize the IoT vision, is to keep the cost low and this can be achieved by having standardized hardware platforms.
3.4. SDN for IoT

with re-configurable software and hardware. A concept that can be used for this is SDN [30].

The advent of new technologies in sensor networks enables re-configuration. Recently, ARM has released more sophisticated micro-controllers, that are more energy efficient and have more resources in terms of memory and computing power. The wireless modules have improved as well. All these developments enrich the options in terms of software which in its turn enable a higher degree of re-configuration and in-network processing. This offers higher level of robustness due to more independence on remote nodes or gateways, lower delays and more energy efficient operation because of the optimized communication paths. An example that is fitting in our approach is having a CCA mechanism that will have the option to be re-configured regarding the source of CTI that occurs.

3.4.1 Research question

As we mentioned before, re-configuration is a way to use commodity hardware in the full range and adapt in different application scenarios. The research question we try to answer here is how SDN principles can be applied in sensor networks to offer re-configuration properties. In other words, how can we use SDN techniques in order to apply software re-configurations and meet the IoT application requirements for different use cases? The approach we describe can lead to use the commercial hardware an wider range and more energy-efficient.

3.4.2 SDN architecture for tailoring IoT devices

Figure 3.5 (from paper III) depicts the proposed network architecture. Each node includes a local controller, which is responsible to receive and execute commands from the central controller. The communication between the central controller and the nodes is carried out either by a routing protocol or with lightweight network schemes, such as network-wide flooding [31]. The central controller may be used to run several services in the network, including topology control, optimization, etc.

Figure 3.6 illustrates the architecture of an SDN-enabled sensor node. The local controller’s main responsibility is to setup, re-configure and monitor the parts of the software that can be reconfigured. The re-configuration can be applied either by changing some parameters in different functions, for instance the transmission power in the radio or by installing new code by using Virtual Machines (VMs). One example of a re-configuration function is the CCA mentioned earlier. More specifically, if the network can identify the source of CTI (LoRa, Wifi, etc) it can use a CCA designed for this
Figure 3.5: Overall SDN architecture for IoT sensor nodes

Figure 3.6: The architecture of an IoT sensor node based on SDN principles
Chapter 4

Summary of Papers

4.1 Paper I: Investigating interference between LoRa and IEEE 802.15.4g networks

**Summary:** In this paper, we carry out a systematic investigation on how LPWANs affect each other when they co-exist in the same environment. We focus on two LPWAN platforms, LoRa and Wi-SUN, and we perform experiments with real hardware in highly controlled scenarios.

**Contribution:** The contribution here is a large dataset of measurement results that enabled us to quantify the tolerance of one network to another and find out which parameters are important for the tolerance of CTI on both sides.

**My Contribution:** I am the main author of this paper and I wrote big part of the code to perform the experiments and analyse the results along with Laura Marie Feeney. I did the experiments with Laura Marie Feeney and we wrote the paper together. Martin Jacobsson wrote some sections of the paper and Per Gunningberg helped in revising it at the end.

4.2 Paper II: Improvement of LoRa/IEEE 802.15.4g co-existence

**Summary:** As the use of LPWAN technologies in IoT increases, the interference between these new networks is something that we need to consider. LPWAN platforms bring new characteristics to the IoT ecosystem and are also very heterogeneous. In this paper, we stress that traditional CCA methods are not very effective for LPWAN. Thus, we selected two emerging
LPWANs, LoRa and Wi-SUN, and evaluated the CCA of Wi-SUN against LoRa and proposed an improved CCA.

**Contribution:** The main contribution in this paper is the evaluation of CCA that we carried out with real hardware, which shows that it is not as effective in detecting ongoing LoRa as it is for other technologies. Furthermore, the improvement we propose, tailored for LoRa, increases the accuracy and decreases the energy consumption of Wi-SUN transmission under LoRa interference.

**My Contribution:** I am the main author of this paper and I wrote most of the code to perform the experiment and analyse the results. I wrote the biggest part of the paper and Laura Marie Feeney and Martin Jacobsson helped me on polishing and refine it. Martin Jacobsson helped me on analysing some of the results and contributed a lot on the energy consumption evaluation of the paper. Per Gunningberg took part in some of the discussions of the paper.

### 4.3 Paper III: Using Software-defined Networking Principles for Wireless Sensor Networks

**Summary:** This paper proposes a Software Defined Networking (SDN) architecture for sensor networks. The idea is to use SDN principles to bring flexibility in order to use commodity hardware in a wider range of IoT deployments and application scenarios. In that way, sensor networks can be re-configured only by the software to meet the requirements of each application.

**Contribution:** We illustrate how SDN principles can be applied in sensor networks using off-the-self hardware in order to have flexible re-configuration and in network processing functionality. The paper points out how the architecture can be used for different purposes, such as routing, network management, and others.

**My Contribution:** I was part of the discussions and I contributed in writing some of the parts of the paper. The rest of the contribution here belongs to Martin Jacobsson.
Chapter 5

Conclusion

In this thesis, we mainly explore Cross Technology Interference (CTI) issues which occur when different Low Power Wide Area Networks (LPWANs) co-exist in the same environment. The long range communication of these networks raises new issues when it comes to co-existence. Furthermore, the low bitrate used in this context, makes reliability and robustness more necessary features. The fact that there is a vast heterogeneity between these networks in terms of radios, communication protocols, and modulation makes it very challenging to achieve a coordination that leads to a sustainable use of the spectrum.

The first part of this thesis is based on a systematic co-existence evaluation of two emerging LPWAN platforms, namely LoRa and Wi-SUN. This part illustrates a representative picture on what happens when these two networks use the same frequency and how much they can tolerate each other. In addition, since we try different configurations in the experimental scenarios, we identify LoRa parameters (i.e. spreading factor and bandwidth) that significantly affect CTI. These insights are important for designing collision avoidance mechanisms.

Another part of the thesis provides an evaluation and improvement of the Wi-SUN Clear Channel Assessment (CCA) mechanism’s ability to accurately detect LoRa transmissions. Under a series of experiments with real hardware, we showed that the Wi-SUN CCA is not able to effectively detect LoRa transmissions. Our measurements indicate that the default CCA identifies correctly the channel as busy only 53% of time. We propose an improvement on the design that is able to detect almost 80% of LoRa transmissions, with a small increase in spurious detections. Moreover, we carried out an evaluation in terms of energy consumption and showed that the improved version consumes less energy since we avoid a number of collisions with the price of increased delay.
In the final part of this thesis, we present an architecture on adapting MAC, PHY and Network configurations in sensor networks by using Software Defined Network (SDN) principles. We mainly discuss how sensor networks can benefit from an architecture like this and what the challenges are.

In future work, we plan to use more LPWAN technologies in our effort such as, Sigfox and NB-IOT, to have a more complete view of their CTI, i.e., how the different LPWAN technologies affect each other. Furthermore, we plan to explore a inter-technology communication protocol among LPWANs that can increase the coordination and thereby address the CTI issues even better.
Bibliography


Part II

Papers
Paper I
Investigating interference between LoRa and IEEE 802.15.4g networks
Investigating interference between LoRa and IEEE 802.15.4g networks

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Abstract

The rapid growth of new radio technologies for Smart City/Building/Home applications means that models of cross-technology interference are needed to inform the development of higher layer protocols and applications. We systematically investigate interference interactions between LoRa and IEEE 802.15.4g networks. Our results show that LoRa can obtain high packet reception rates, even in presence of strong IEEE 802.15.4g interference. IEEE 802.15.4g is also shown to have some resilience to LoRa interference. Both effects are highly dependent on the LoRa radio’s spreading factor and bandwidth configuration, as well as on the channelization. The results are shown to arise from the interaction between the two radios’ modulation schemes. The data have implications for the design and analysis of protocols for both radio technologies.

1 Introduction

We present a systematic measurement study of Cross-Technology Interference (CTI) between LoRa and IEEE 802.15.4g networks. Using controlled interference scenarios, we are able to quantify each network’s resilience to CTI and explain their behavior in terms of their respective modulation.

Both technologies use unlicensed spectrum that may be freely used by anyone, subject to regulatory constraints on transmit power and spectrum utilization. Operating in unlicensed spectrum is attractive because both network providers and individual users can deploy and use wireless devices without complex and costly administrative overhead. This flexibility has enabled the development of many applications that are becoming part of daily
life. As a result, there are an increasing number of independent networks operating at the same location, using the same unlicensed spectrum and hence competing for transmission time. These networks are very diverse, with radios and communication protocols that are variously optimized for high data rates, long range, low power consumption, or high reliability.

Future smart building and smart city IoT applications will therefore need to be able to operate reliably in an environment where interfering networks use the shared spectrum in very different ways. Understanding and mitigating the impact of cross-technology interference among heterogeneous networks is therefore an important challenge.

LoRa (Long Range) [1] is a recently developed sub-GHz low-power wide-area network (LPWAN) technology. It uses a proprietary modulation to obtain high receiver sensitivity and achieve long-range, low-bitrate communication. One of its main use cases is as an infrastructure network providing simple uplink capability for low power consumption devices. Another popular sub-GHz radio technology is IEEE 802.15.4g [2], an IEEE 802.15.4 [3] PHY layer developed in the context of Smart Utility Network applications [4]. It provides higher data rates and correspondingly shorter range than LPWAN solutions. Since both technologies are likely to be used simultaneously in urban areas, it is important to investigate the impact of their interference on each other.

Several papers have studied LoRa communication performance and scalability with respect to interactions within and between LoRa networks. To the best of our knowledge, this paper is the first to present a systematic measurement study of the interactions between LoRa and IEEE 802.15.4g networks operating in the EU 868 MHz unlicensed spectrum.

By creating highly controlled scenarios where transmitted packets are exposed to (almost) continuous interference, we are able to quantify the impact of interference on the Packet Reception Rate (PRR) in both networks. Our results show that LoRa is resilient enough to get high PRR even when the strength of an interfering IEEE 802.15.4g signal is considerable higher than the LoRa signal strength at the receiver. At moderate data rates, the LoRa PRR is almost unaffected by a 16 dB higher interference signal from IEEE 802.15.4g. Even at LoRas highest data rate settings it seems to tolerate up to 6 dBm of IEEE 802.15.4g interference.

IEEE 802.15.4g is more sensitive than LoRa to interference, but this depends very much also on the settings of the LoRa parameters, not only the power level since LoRa is sweeping over the IEEE 802.15.4g frequencies. We explain the interaction behaviors in terms of interference power, LoRa radio configuration parameters (notably the bandwidth and spreading factor), and the two radios modulation schemes.

Our contributions are useful for at least three purposes: First, our re-
results can influence future work in cross-technology interference mitigation. Second, they can be used to parameterize and validate interference models and simulations. Finally, our work can inform future regulations on how to effectively share unlicensed spectrum.

The paper is organized as follows: Sections 2 and 3 describe the state of the art and provide background about these radio technologies. Section 4 describes our methodology and presents the results and Section 5 concludes the paper.

2 Related Work

There are numerous LPWAN technologies emerging. LoRa, in particular, has attracted both research and industry interest because of its long range and robust performance. Existing research mostly focuses on LoRa performance, especially its transmission range, capacity, and scalability and on interaction between LoRa transmissions. They include [5–7], where the authors evaluate LoRa performance under various set of configurations and conditions. For instance, [5] introduces an algorithm for selecting proper parameters considering a desired energy consumption and link quality. In [7], a measurement study shows that vegetation has a big impact on LoRa transmissions. The Spreading Factor (SF) and the transmission data rate have a significant impact on the network coverage according to [6].

LoRa scalability is investigated in [8–10]. The authors in [8] analyze a LoRa network using a single gateway. Their results show that with an increase in the number of end-devices, the coverage probability drops exponentially, due to their interfering signals. In [9], simulation is used to show that multiple base stations improves the network performance under interference. In [10], the authors focus on the performance impact of LoRa on higher layers. Notably from their work is that the down-link receive window is seen as the limiting factor. This work, like the others, identifies that the main scalability limit of LoRa is its channel access protocol (essentially ALOHA) together with its rather expensive packet acknowledgements.

Finally, the work most closely related to ours is [11], an empirical study of interference between LoRa networks (a pre-print at the time of this writing). The paper investigates the interference case when one LoRa radio uses conventional LoRa modulation and the other one uses 2-GFSK modulation, which is also used in IEEE 802.15.4g. (Support for 2-GFSK is required in the LoRa specification.) The experiments use randomized packet lengths and inter-arrival times for both the sender and the interferer. The inter-arrival times are a significant fraction of (and in some cases longer than) the packet transmission times. This means that the proportion of time that
the channel is interfered varies depending on the choice of LoRa transmis-

sion parameters. As a consequence, the results reflect a mix of heavily and

minimally interfered packets. It is therefore hard to draw conclusions about

the interference behavior, beyond the specific empirical observations. By

contrast, we are doing much more controlled experiments that allow us to

examine the interaction between the two modulations in detail.

3 Background

In this section, we give the necessary background information about LoRa,

IEEE 802.15.4g, and the spectrum overlap of these two wireless technologies.

3.1 LoRa

LoRa [1] uses a proprietary modulation scheme by the company Semtech

based on Chirp Spread Spectrum (CSS), which is both energy efficient and

can achieve long distance transmissions. Chirp Spread Spectrum (CSS) is

a spread spectrum technique, using wideband linear frequency modulated

chirp pulses to represent information. A chirp is a sinusoidal signal whose

frequency increases or decreases linearly over time. Information is encoded

in the sequence of frequencies present in each chirp. The LoRa operating fre-

quencies in Industrial, Scientific, and Medical radio band (ISM) are EU:868

MHZ and 433 MHz, USA:915 MHz and 433 MHz. The bit rate, range, and

resilience to interference are determined by the configuration parameters of

LoRa, which are listed below.

**Carrier Frequency**: Carrier Frequency (CF) determines the central trans-

mission frequency. The range for LoRa device we used, Semtech XRange

SX1272 [12], is from 860 to 1020 MHz.

**Bandwidth**: The Bandwidth (BW) is the distance between the lowest and

highest frequency in each chirp. A higher BW will increase the data rate

and decrease the transmission time on air for a packet. It will also decrease

the decoding sensitivity, since the radio signal is exposed more to noise. Us-

ing a low BW for the same size packet means longer transmission time and

a higher risk that receiver will fall out of synchronization due to imperfect

receiver clock drift. According to the specifications of the SX1272 modem,

the available values for the BW are 125, 250 and 500 kHz.

**Spreading Factor**: Spreading Factor (SF) [13], is the ratio between the

chip rate and the underlying the symbol rate. If we increase the SF (i.e.

more bits per symbol), the Signal to Noise Ratio (SNR) will be increased

and consequently it will increase the range and the sensitivity, but also the

time on air to send a symbol. The values available for this parameter are

from 6 to 12 and the number of chips per symbol can be computed as $2^{SF}$. 


For instance, with the value of 7 (SF7), we get 128 chips per symbol. Different SF can be used to separate transmission as they are orthogonal to each other.

**Coding Rate:** LoRa uses Forward Error Correction (FEC) for the payload. The level of FEC is set by the Coding Rate (CR) parameter. CR increases robustness against interference but increases the time on air when more redundant bits are used for corrections.

### 3.2 IEEE 802.15.4g

The IEEE 802.15.4 [3] is the standard for Low-Rate Wireless Networks. It operates in several different bands, including the popular 2.4 GHz band. Today, there is an increased usage in the sub-GHz bands. The IEEE 802.15.4 standard defines several different modulation schemes in the sub-GHz band. One important variant is the IEEE 802.15.4g (called SUN, Smart Utility Network, in the latest IEEE 802.15.4 standard), in the 863-870 MHz band, overlapping the LoRa frequencies. In this band, SUN uses up to 34 non-overlapping channels with 200 kHz spacing. SUN Mode # 1, achieves a data rate of 50 kbps using a bandwidth of 110 kHz with a frequency deviation of 50 kHz, which is the default configuration. SUN uses Frequency Shift Keying (FSK) or Gaussian Frequency Shift Keying (GFSK) modulation.

### 3.3 Spectrum Overlap

Both LoRa and IEEE 802.15.4g (SUN) operate in the 868MHz license-free bands. There is both partial and complete overlap between the two technologies depending on the configurations of the two radios. We use 868.3 MHz as the LoRa center frequency, which allows us to use all three LoRa BWs. The overlap between LoRa and 802.15.4g standard is depicted in Fig. 6.

Fig. 1 presents the case when an IEEE 802.15.4g transmission collides with a LoRa transmission. In Fig. 1a, we see packet transmission from an IEEE 802.15.4g transmitter with 2-Level GFSK modulation with transmission power 12 dBm and in Fig. 1b, LoRa transmission with SF12, BW 125 kHz with transmission power 12 dBm. In Fig. 1c, LoRa completely overlaps the IEEE 802.15.4g packet as a superimposing of the transmissions. This is the main case we will investigate thoroughly in the next section of the paper.

### 4 Experimental Evaluation

This section describes our systematic measurement studies of the interaction between LoRa and IEEE 802.15.4g radios operating in 868 MHz spectrum.
(a) IEEE 802.15.4g packet, output power 12 dBm at channel 26 (868.325 MHz). The channel is 200 kHz wide, with two sharp peaks separated by 50 kHz for the 2-GFSK modulation.

(b) LoRa packet with output power 12 dBm. The LoRa is configured for bandwidth 125 kHz and spreading factor SF12, centered at 868.3 MHz.

(c) IEEE 802.15.4g and LoRa packet collision, the LoRa packet overlaps the other packet.

Figure 1: LoRa and IEEE 802.15.4g packet illustrated separately (1a, 1b) and when they collide (1c) captured by the Software Defined Radio (SDR). The vertical line shows the center capturing frequency for the SDR, which was 868.3 kHz.
Details of the experimental setup are presented in section 4.1. We report on two groups of experiments: IEEE 802.15.4g communication subject to LoRa interference (section 4.2) and LoRa communication subject to IEEE 802.15.4g interference (section 4.3).

In each experiment, we measure the packet PRR between a transmitter and receiver in the presence of interfering transmissions from the other radio. Each radio occupies the channel as much as possible, maximizing collisions and allowing us to focus on low-level interactions between the two radios. To do this, we disabled the Channel Sensing and the MAC protocol on both the IEEE 802.15.4g and LoRa radios. Both the sender and the interferer were configured to transmit with a minimum gap between packets. This ensures that all packets experience interference over essentially their entire transmission time.

Our experiments were performed in an anechoic chamber, which is a radio isolated environment. This eliminates external interference and allows us to perform many hours of nearly continuous transmission, which spectrum regulations would otherwise make infeasible. The disadvantage of this approach is that the distances between radios are necessarily limited by the dimensions of the chamber. Our results therefore reflect relatively high signal strengths for both transmissions and interference. (Experiments using highly attenuated signals, operating closer to the limits of receiver sensitivity are deferred to future work.)

As we noted in Section 3, LoRa and IEEE 802.15.4g have quite different channelization and modulation. In particular, there are two LoRa configuration parameters, SF and BW, that define timing patterns in the channel utilization. We therefore vary these parameters, along with the transmission power, to understand how these radios interfere with each other with respect to the parameters.

4.1 Experiment Setup

The LoRa radios are Semtech XRange SX1272 [12], equipped with a 3 dBi whip antenna. The host computer for the Semtech radio is Netblocks[14], running a variant of the lorablink [15] software, based on the freely available IBM/Semtech Lmic v1.6 [16] software. This software provides “bare-metal” access to the radio, allowing us fine-grain control of the transmission parameters and timing.

The LoRa packets contain a random payload of 59 B, an implicit header and a CRC checksum. The transmit time of the packet depends on the combination of LoRa parameters (SF, BW, CR) that are shown in Table 1. The CR value we use is 4/5. The interval between packet transmissions is 576 µsec, measured with an SDR [17] module.
Table 1: Transmit time (ms) for a LoRa packet with 59 B payload for coding rates 4/5 and 4/8 (minimum and maximum redundancy, respectively). Each packet has an implicit header and a CRC checksum. Values from the Semtech LoRa Modem Calculator Tool [18].

<table>
<thead>
<tr>
<th>SF</th>
<th>CR 4/5</th>
<th>CR 4/8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW125 BW250 BW500</td>
<td>BW125 BW250 BW500</td>
</tr>
<tr>
<td>7</td>
<td>108 54 27</td>
<td>160 80 40</td>
</tr>
<tr>
<td>8</td>
<td>195 98 49</td>
<td>287 144 72</td>
</tr>
<tr>
<td>9</td>
<td>340 175 87</td>
<td>509 254 127</td>
</tr>
<tr>
<td>10</td>
<td>657 329 162</td>
<td>952 476 238</td>
</tr>
<tr>
<td>12</td>
<td>2302 1151 575</td>
<td>3285 1642 821</td>
</tr>
</tbody>
</table>

The IEEE 802.15.4g radios are Texas Instruments CC1310 Launchpad [19], with a PCB antenna whose gain is 3.61 dBi. The nodes run Contiki OS [20]. The Contiki MAC and radio duty cycle are disabled to ensure minimum time gap between transmissions. Each IEEE 802.15.4g packet has a random payload of 106 B plus header and a CRC-16. The transmit time for each packet is a constant 21.18 msec and the interval between packets is 416 µsec, measured with an SDR module.

As a result, all packets are exposed to interference from the other radio technology for essentially their entire duration. The LoRa packet transmit time is longer than the IEEE 802.15.4g packet transmit time. Each LoRa packet will therefore experience between one and sixty 416 µsec gaps between interfering IEEE 802.15.4g transmissions. However, the interfering IEEE 802.15.4g transmissions still occupy the channel over 98% of the time.

Conversely, an IEEE 802.15.4g packet will experience at most one gap between interfering LoRa transmissions. This gap is 576 µsec long, so an IEEE 802.15.4g packet will experience interference for at least 97% of its 21.18 msec transmit time.

We therefore consider packets as being continuously interfered in our analysis. In addition, we collect a sample of at least 100 interfered packets in each configuration. This ensures that any gaps in the interference occur at different times during packet transmission. In particular, the synchronization header is not specifically targeted or avoided with interference. This approach allows us to avoid requiring tight synchronization between the two radios to create interference scenarios.

4.2 LoRa interfering on IEEE 802.15.4g communication

Our first set of experiments examines how LoRa interference affects IEEE 802.15.4g communication. The IEEE 802.15.4g sender and receiver are
Figure 2: Heat-map of IEEE 802.15.4g PRR under LoRa interference. On the x-axis are depicted a set of channels for IEEE 802.15.4g (24–28) which are repeated for each transmission power value of 802.15.4g. On the y-axis is depicted the LoRa interference TX power in dBm. The values on the top denote the transmission power of the 802.15.4g transmitter in dBm. For instance, the leftmost bottom block at subfigure 2a illustrates that the PRR was 100% at channel 24 when the IEEE 802.15.4g transmission power was 2 dBm while the LoRa interference power was 2 dBm, the SF was 7 and the BW 125 kHz.
placed 6.4 m apart in an anechoic chamber, 80 cm above the inner floor of the chamber. The LoRa interferer is placed 10.5 m away from the receiver. All nodes are in line-of-sight (Fig. 3a) and the printed circuit board antennas on the IEEE 802.15.4g nodes are directed to face each other.

Table 2 shows the average received power measured at the position of the 802.15.4g receiver, for various output power settings at the 802.15.4g sender and again for the same output power settings at the LoRa interferer. The measurements were made manually, using a Keithley 2810 vector signal analyzer equipped with a 3 dBi whip antenna. The uncertainty is approximately ± 1 dBm. The PCB antenna on the IEEE 802.15.4 receiver has a different gain than the antenna on the signal analyzer, so the measured power is not exactly the same as the power received by the IEEE802.15.4 radio. However, since both the interference and transmission power are measured using the same antenna (whether it is the signal analyzer or the IEEE 802.15.4 receiver) in each case, the ratio between the two power levels will be the same. The differences between the received and interfering powers obtained in this experiment layout range from -6dB to -24dB. As expected, the measured LoRa interference power does not depend on the BW parameter.

<table>
<thead>
<tr>
<th>output</th>
<th>LoRa interference power measured (dBm)</th>
<th>IEEE 802.15.4g TX power measured (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW 125</td>
<td>BW 250</td>
</tr>
<tr>
<td>12</td>
<td>-36</td>
<td>-36</td>
</tr>
<tr>
<td>10</td>
<td>-38</td>
<td>-39</td>
</tr>
<tr>
<td>8</td>
<td>-40</td>
<td>-40</td>
</tr>
<tr>
<td>6</td>
<td>-42</td>
<td>-42</td>
</tr>
<tr>
<td>4</td>
<td>-44</td>
<td>-44</td>
</tr>
<tr>
<td>2</td>
<td>-45</td>
<td>-48</td>
</tr>
</tbody>
</table>

Table 2: TX power setting of the LoRa interferer, 802.15.4g transmitter and the resulting interference power and transmitting power measured at the IEEE 802.15.4g receiver.
4.2.1 Packet Reception Rate under LoRa interference

From our previous discussion, we expect that the PRR of IEEE 802.15.4g will vary with the relative received power from the two radios. A high BW of LoRa will affect more than one IEEE 802.15.4g channel and the SF of LoRa will be insignificant since it is intended to change the LoRa effective data rate without changing the BW or overall power.

Our PRR measurement results are presented in Fig. 2 as sets of “heatmap blocks”. Each set of blocks represents one combination of BW and SF values. Each block represents a different IEEE 802.15.4g transmission power level, from 2 to 12 dBm. Within each block, the PRR "heat" level is illustrated with different blue colors, from white for zero received packets up to dark blue for 100% correctly received packets. The PRR color is given for IEEE 802.15.4g packets sent using each of five IEEE 802.15.4g channels, 24 to 28, marked on the x-axis in each block. For each block the LoRa interference power is varied from 2 to 10 dBm, given on the y-axis. The strength of the LoRa interferer relative to the IEEE 802.15.4g packet transmission can be inferred from the received power measurements in Table 2. The frequencies used by the IEEE 802.15.4g sender and the LoRa interferer are shown in Fig. 6.

Starting with the leftmost sub-block in Fig. 2a, we see that LoRa severely interferes with channel 26 of IEEE 802.15.4g. The measured PRR on that channel became very close to zero, even at low LoRa power levels. The BW of LoRa is 125 kHz, which means that the interference band is confined to channel 26. The other channels around 26 are unaffected and consequently the measurements reached the highest PRR level, independent of the LoRa output power level. As the IEEE 802.15.4g transmit power increases (the
rightmost sub-blocks in Fig. 2a), some packets are successfully received on channel 26, for the lowest levels of LoRa interference. The PRR becomes non-negligible once the LoRa interference is no more than 6-7dB higher than the received power.

Measurements with the LoRa BW set to 250 and 500 kHz respectively are reported in Figs. 2b-2c. As expected, LoRa’s now larger band will interfere up to four IEEE 802.15.4g channels for the 500 kHz case (each channel is 200 kHz wide). The overall PRR pattern is though similar to the 125 kHz case but now the LoRa power is spread over more channels. Thus, for the stronger IEEE 802.15.4g power settings some higher PRR is achieved compared to the 125 kHz case.

The SF factor values used are 7 to 10 in Fig. 2. When comparing the PRR for different SF over the 125, 250 and 500 kHz cases respectively we see similar PRR patterns for each bandwidth which confirms our general hypothesis that the SF parameter has a relative small impact on the IEEE 802.15.4g transmission. The details and actual interactions will be further discussed below.

### 4.2.2 Discussion of the BW impact

With the LoRa center frequency set to 868.3 MHz, LoRa’s 125 kHz BW interferes with a substantial portion of the 200 KHz wide IEEE 802.15.4g channel 26 (Fig. 6), resulting in substantial packet loss on that channel. When the LoRa BW is 250 kHz, a portion of IEEE 802.15.4g channel 25 also experiences interference. Some IEEE 802.15.4g packets sent on this channel are successfully received once the LoRa interference is no more than around 12-14dB higher than the received power, depending also on the SF (see below). When the BW is 500 kHz, up to four IEEE 802.15.4 channels are affected. Again, the channels experiencing the largest overlap suffer the most.

### 4.2.3 Discussion of the power impact

When the transmission power at IEEE 802.15.4g transmitter is increased, some packets are successfully received. For instance, if we compare the min and max output power for IEEE 802.15.4g in Fig. 2a when LoRa is interfering at 2 dBm the PRR goes from 0% to 74%. The interference level for that case is 6 dB high, even though some packets from the IEEE 802.15.4g transmitter are successfully received. This happens because LoRa uses CSS modulation, which means that the transmitted signals are chirps, which change frequency continuously in order to represent the requested symbol. On the other hand IEEE 802.15.4g uses 2-Level GFSK modulation which
Table 3: TX power setting of the LoRa sender, IEEE 802.15.4g interferer and the resulting transmitting and interference power measured at the LoRa receiver.

<table>
<thead>
<tr>
<th>output</th>
<th>LoRa TX power measured (dBm)</th>
<th>IEEE 802.15.4g interference power measured (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW 125 BW 250 BW 500</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-34 -35 -36</td>
<td>-29</td>
</tr>
<tr>
<td>10</td>
<td>-36 -38 -37</td>
<td>-31</td>
</tr>
<tr>
<td>8</td>
<td>-38 -40 -42</td>
<td>-31</td>
</tr>
<tr>
<td>6</td>
<td>-41 -41 -40</td>
<td>-34</td>
</tr>
<tr>
<td>4</td>
<td>-43 -44 -45</td>
<td>-36</td>
</tr>
<tr>
<td>2</td>
<td>-44 -45 -45</td>
<td>-40</td>
</tr>
</tbody>
</table>

uses two different frequencies to transmit 0 or 1. When the chirp is not completely at the same frequency with the GFSK signal and the power in GFSK is strong enough, the packets are successfully received and not affected from the interference.

![Image](a) SF7 BW500 kHz  ![Image](b) SF8 BW500 kHz

Figure 4: Illustration of how the angle of the chirp changes when we change the SF in LoRa captured from the SDR. Time is along x-axis and frequency in y-axis.

### 4.2.4 Discussion of the SF impact

The PRR in IEEE 802.15.4g also decreases slightly with increasing SF in the LoRa interference. This is noticeable for BW 250 kHz and especially BW 500 kHz (Figs. 2c, 2f, 2i and 2l). An explanation of this behaviour is that when the SF increases, the angle of the chirp becomes shallower and overlaps more with the GFSK signal. Fig. 4 shows the angle difference of SF7 and SF8 chirps. With a larger SF, the degree of tolerance from IEEE 802.15.4g decreases because the two signals overlap more. Fig. 2c shows that when the difference between the interference power to transmission power is 7 dB.
and the SF is 7, the PRR is around 90% for channels 25-27. For the same configuration, but an SF of 10, Fig. 2l shows that two of the three interfered channels have 0% PRR and channel 27 drops to 73% PRR.

4.3 IEEE 802.15.4g interfering on LoRa communication

The second set of experiments examines how IEEE 802.15.4g interference affects LoRa communication. The LoRa transmitter and receiver are placed 11.7 m apart in an anechoic chamber, 80 cm above the inner surface of the chamber. The IEEE 802.15.4g interferer is 1.5 m away from the LoRa receiver and its printed circuit antenna is directed toward the LoRa receiver. All nodes are in line-of-sight (Fig. 3b).

Table 3 is the analog of Table 2. It shows the average power received at the position of the LoRa receiver, for various output power settings at the LoRa sender. Table 3 also shows the received power of the interfering IEEE 802.15.4g transmissions at the position of the LoRa receiver. The measurements were made manually using a Keithley 2810 vector signal analyzer; the uncertainty is approximately ±1-1.5 dBm.

4.3.1 Packet Reception Rate under IEEE 802.15.4g interference

Fig. 5 presents a set of PRR heatmaps similar to those in Fig. 2. Each of the subfigures represents a LoRa radio configuration (SF and BW). Within each subfigure, each block represents a transmission power level of the IEEE 802.15.4g interferer. The same power is used on all channels 24 to 28, represented on the x-axis. The LoRa transmit power levels are given on the y-axis. The ”blue heat color” of each small sub-block shows the PRR, i.e. the proportion of correctly received LoRa packets, for a given LoRa output power and IEEE 802.15.4g interference power and channel.

LoRa packets are – as expected – significantly more resilient to interference than IEEE 802.15.4g packets. For spreading factor SF9 and above, packet losses become negligible, even when the interferer is ~16 dB stronger according to the difference between LoRa and IEEE 802.15.4g interference power in Table 3. Even at lower spreading factors and bandwidths, LoRa still obtains acceptable PRR when the interferer is 6 dB stronger.

4.3.2 Discussion of the LoRa PRR results

To some extent, the LoRa resilience can be explained by trading lower data rates against redundancy using higher spreading factors. This is in contrast to the experiment in the previous section, where the IEEE 802.15.4g packets have a fixed 50 kbps data rate.
(a) SF 7, BW 125 kHz (5.5 kbps)  
(b) SF 7, BW 250 kHz (10.9 kbps)  
(c) SF 7, BW 500 kHz (21.8 kbps)  
(d) SF 8, BW 125 kHz (3.1 kbps)  
(e) SF 8, BW 250 kHz (6.2 kbps)  
(f) SF 8, BW 500 kHz (12.5 kbps)  
(g) SF 9, BW 125 kHz (1.8 kbps)  
(h) SF 9, BW 250 kHz (3.5 kbps)  
(i) SF 9, BW 500 kHz (7.0 kbps)

Figure 5: Heat-map of LoRa PRR under IEEE 802.15.4g interference. The figure is similar to Figure 2, but now the IEEE 802.15.4g power and channels (x-axes) reflect the interference and the LoRa power (y-axes) reflects the interfered packets. The LoRa data rate doubles (left to right) as the bandwidth doubles and decreases by about half for each increase in spreading factor (top to bottom). In the lower left of each figure (LoRa TX power 6 dBm, IEEE 802.15.4g TX power 12 dBm), the interfering signal is about 7 dB higher at the receiver. In the upper right of each subfigure (LoRa TX power 2 dBm, IEEE 802.15.4g TX power 12 dBm), the interference is about 16 dB higher.

Figure 6: 868 MHz unlicensed spectrum. LoRa (above) is configured to operate at a 868.3 MHz center frequency. The 3 BWs are shown. The IEEE 802.15.4g standard defines fixed channels (below). The channel spacing and the 2-GFSK frequency deviation (solid dots) are shown for each channel. The output power is highest at these two points (corresponding to the peaks in Figure 1a).
The trade-off becomes visible when comparing the PRR for LoRa configurations with similar data rates but with different BW and SF factors, see Figs. 5i and 5e, or 5f and 5b. LoRa is more vulnerable to interference when using low bandwidth combined with a small spread factor.

Another contributing factor to the LoRa resilience is its modulation. LoRa uses CSS modulation in contrast to GFSK used by IEEE 802.15.4g. CSS spreads the energy of the symbol across the whole bandwidth while GFSK concentrates the energy to two shift frequencies making 802.15.4g more sensitive to narrowband interference. Their spread can be seen in Fig. 1a and Fig. 6.

5 Conclusion

We have evaluated the impact of cross-technology radio interference between LoRa and IEEE 802.15.4g networks with real experiments focusing on the PRR metric. In general, we conclude that LoRa is much more tolerant than IEEE 802.15.4g under interference and LoRa’s radio configuration (SF and BW) are important to the degree of tolerance. At a high data rate setting, LoRa can tolerate interference power that is 6 dB higher than the actual LoRa receiving power and for the low data rate it can tolerate up to 16 dB with acceptable PRR. IEEE 802.15.4g seems to be resilient to LoRa interference under some certain configurations of LoRa. More specific, IEEE 802.15.4g has some tolerance to LoRa which is depending on the parameters SF and BW. The significance of the results comes from the fact that they give insights in both radio platforms, which could help designing collision avoidance mechanisms and provide reliability and robustness to the higher layers. Such designs we leave for further work.

Acknowledgement

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References


Paper II
Improvement of LoRa/IEEE 802.15.4g co-existence
Improving LoRa/IEEE 802.15.4g co-existence

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Abstract

Widespread use of LPWAN technologies in unlicensed spectrum will lead to high levels of interference between independent co-existing networks. In this work, we study cross-technology interference between LoRa and Wi-SUN (IEEE 802.15.4g) networks. We use hardware experiments to show that the default Wi-SUN clear channel assessment (CCA) mechanism does not reliably detect interfering LoRa transmissions and propose a more effective alternative.

1 Introduction

The advent of Low Power Wide Area Network (LPWAN) technologies promises to enhance the IoT with new features such as long range communication, robustness and low energy consumption. These features enable new application scenarios such as smart cities, smart agriculture, building management and many more. However, the popularity of these technologies means that many networks may be operating independently in the same location. LPWAN technologies have low data-rates and use unlicensed spectrum. Interference between these networks is therefore inevitable and may degrade the performance. In particular, cross-technology interference (CTI) poses special challenges.

In this work, we study the co-existence of Wi-SUN (IEEE 802.15.4g) and LoRa. LoRa is a popular smart city networking technology and Wi-SUN is a popular smart utility networking technology. Both operate in the same sub-GHz band. In a previous work [1], we found that both LoRa and Wi-SUN are affected when they operate in the same area, but mostly Wi-SUN, since LoRa is more robust to interference.
The IEEE 802.15.4 standard [2] used by Wi-SUN uses a CSMA based media access control layer and defines a clear channel assessment (CCA) mechanism based on channel sensing. A sender checks whether the channel is occupied before sending. If it detects an ongoing transmission, it uses a random back-off procedure to avoid a collision.\textsuperscript{1}

However, different kinds of radios may use the shared channel very differently. It can be difficult for one radio to detect transmissions from a radio that uses a different channelization or modulation and this can reduce the effectiveness of CCA-based collision avoidance methods. Accurate CCA is therefore is a necessary step in reaching proper co-existence.

The main contribution of this paper is to characterize and improve the effectiveness of the Wi-SUN CCA mechanism in detecting ongoing LoRa transmissions. We answer the following questions. How accurate is Wi-SUN’s CCA method when it comes to detecting LoRa transmissions? And how can it be improved?

We describe a systematic series of experiments with real hardware and highly controlled system using an RF combiner and attenuators to regulate the power levels and eliminate any source of external interference. We measure the effectiveness of the Wi-SUN default CCA mechanism for a variety of LoRa modulation parameters. We observe that the CCA mechanism can detect interfering LoRa transmissions only 53\% of the time and explain this in terms of LoRa modulation. We propose an enhanced CCA mechanism that is almost 80\% accurate at detecting levels of LoRa interference that will result in packet loss due to collision. The proposed mechanism is largely compatible with the existing CSMA mechanism, has only a small increase in spurious detections and, does not reduce the ability of Wi-SUN to detect other Wi-SUN transmissions. We also show that the enhanced CCA reduces energy consumption by almost 8\%.

2 Related Work

Enhancing the CCA mechanism or proposing a collision avoidance mechanism are popular topics in low power wireless communications, which have been researched a lot in the past. An early CCA design can be found in [3]. Here a Received Signal Strength Indicator (RSSI) value is sampled when the radio is not used and it is stored in a FIFO queue. Then, the noise floor is calculated with an exponentially weighted moving average (EWMA). The result shows that by following such a method, the throughput can be doubled in comparison with the traditional methods of that time.

\textsuperscript{1}LoRa radios do not sense the channel, but instead rely on duty cycle limits to achieve co-existence.
A recent work from Sparber et al. [4] proposes Dynamic CCA, a mechanism that dynamically modifies the threshold in the CCA procedure for the t-mote sky platform. With the introduced approach, they managed to improve the Packet Received Ratio (PRR), which is the ratio between the received and sent frames, and the energy consumption of the network. Another work that adapts the energy-level threshold used by the CCA mechanism is presented in [5]. In this approach, the main goal is to reduce the false wake up by the sensor network nodes. The authors propose a design of the CCA mechanism for Low Power Listening, where the energy detection threshold is dynamically adjusted based on application-specific requirements. The results show that the impact of interference on the duty cycles is decreased while still maintaining the link reliability.

CCA in the presence of CTI has also been studied. For example, Yuan et al. in [6], introduced a CCA mechanism for IEEE 802.15.4 where the threshold is dynamic, targeting the common situation when it co-exists with a IEEE 802.11 network, which uses much higher transmission power. When the interference is significantly increased, the threshold is increased as well in order to avoid collisions. Simulations indicate that the throughput can be improved with the proposed design and without affecting the energy consumption of the network.

Also [7] studied the CTI between IEEE 802.11 and IEEE 802.15.4. By proposing to differentiate the operation of CCA regarding the source of interference, they proved that the throughput can be improved. More specifically, the authors tested the performance of a CCA mechanism that tries to identify the source of interference and then, depending on the type of source, reacting with a tailored mechanism against it.

However, to best of our knowledge, scientific literature does not yet cover the CCA mechanisms within the LPWAN field except a few related cases. Such a case is [8], where the authors are exploring how to improve the reliability of weak backscatter links for wide area backscatter networks. In their paper, they evaluated how the filter bandwidth is affecting the received signal, but instead of LoRa signal they tested with an unmodulated carrier.

Even though that there are multiple scientific papers investigating how CCA can be improved in the sensor network community, the arrival of LPWAN calls for new solutions, since the requirements and the technology are different. In this paper, we will contribute to this issue and answer some of the questions we raise relative to this topic.
3 Background

In this section, we give the necessary background information about LoRa, IEEE 802.15.4g Wi-SUN, and the CCA mechanism.

3.1 LoRa

LoRa [9] is an LPWAN platform, able to achieve long range communication with high robustness. LoRa is based on a proprietary modulation scheme called Chirp Spread Spectrum (CSS), which enables high sensitivity levels and functions in low-bitrate. LoRa is operating in subGHz unlicensed spectrum. The data rate can range from 0.3 to 21.8 Kbps, the range is 2 – 5 km in urban areas, and the sensitivity is down to –137 dBm. The configuration parameters of LoRa can alter the data rate, robustness and time on air of a signal. A brief overview of these parameters is given below.

**Carrier Frequency:** This parameter defines the central frequency of LoRa transmissions. The available range for the modem we used in this paper is from 860 to 1020 MHz with a resolution of 61 Hz.

**Bandwidth:** Bandwidth (BW) is the domain between the highest and lowest frequency that a chirp can use. The bandwidth value is proportional to the data rate, but inversely proportional to the time on air and decoding sensitivity, because the signal is exposed more time to the noise. The available values for the modem that we used are 125, 250 and 500 kHz.

**Spreading Factor:** Spreading Factor (SF), as it is defined in [10], is the ratio between the number of multiple chips representing the sending information to the symbol rate. The SF is proportional to the Signal to Noise Ratio (SNR) and SNR is proportional with the sensitivity, time on air, and range. The values available for this parameter are from 6 to 12 and the number of chips per symbol can be computed as $2^{SF}$. For example, if the SF value is 7, then a symbol is represented by 128 chips. Different SF values offer orthogonality in LoRa communication.

**Coding Rate:** LoRa uses Forward Error Correction (FEC) for the payload. The Coding Rate (CR) parameter defines the level of FEC. A higher CR offers higher robustness levels against interference, but it also increases the time on air, since there will be more redundant bits.

3.2 IEEE 802.15.4g Wi-SUN

Wi-SUN is a variant from the popular IEEE 802.15.4 [2] standard for Low-Rate Wireless Networks with long range communication up to approximately
500 meters and a data rate up to 300 Kbps. The radio sensitivity is $-124$ dBm. It is operating in the same frequency band with LoRa, which in EU is $863 – 870$ MHz. The standard divides the band in 34 non-overlapping channels, which are 200 kHz wide each. The standard allows for several modulation techniques, however we focus on the popular versions based on Frequency Shift Keying (FSK) or Gaussian Frequency Shift Keying (GFSK) only.

### 3.3 CCA

The CCA mechanism of Wi-SUN is defined as a mechanism in the context of the CSMA/CA (Carrier Sense Multiple Access, Collision Avoidance) context [2]. The CCA marks the channel as occupied from the followings sources: an amount of Energy Detected (ED) above a threshold in the channel, the detection of a signal with the same standard characteristics (i.e., an 802.15.4 packet), or a combination of the two. Only the ED version can be used to detect a LoRa transmission as LoRa uses a different modulation technique. Therefore, we will only focus on ED-based CCA in this work. However, we do not exclude the use of a combination since a complete CCA should be able to detect both LoRa and Wi-SUN transmissions.

### 4 Experimental Setup

Before we can design a better CCA mechanism, we need to understand the co-existence between LoRa and Wi-SUN. In this section, we will first explain our experimental setup and then carry out a few preliminary measurements that try to understand how Wi-SUN CCA behaves in the presence of LoRa
LoRa is shifting in 10 kHz intervals and Wi-SUN is sampling at a fixed channel illustrated with gray background.

transmissions as well as how colliding Wi-SUN and LoRa frames affect each other.

Our experimental platform consists of three nodes connected with an RF-combiner and with attenuator as depicted in Fig. 1. The nodes are connected with a coaxial cable and two attenuators of 36 dB each to mitigate the signal power from the radio. We used two Wi-SUN nodes, one acting as transmitter and the other as receiver, and a LoRa node acting as interferer. The Wi-SUN nodes operate on a fixed channel, while we change the central frequency of the LoRa transmitter to also experiment with partial overlapping channels.

The Wi-SUN nodes were Texas Instruments CC1310 Launchpad [11] running Contiki-OS [12]. The ContikiMAC and radio duty cycle functions were disabled to enable minimum time gap (416 µ sec) between transmissions. Each Wi-SUN frame had a random payload of 80 B plus header and a CRC-16 checksum.

The LoRa node was Semtech XRange SX1272 [13] on a platform developed by Netblocks [14]. We used lorablink [15] as the operating system, which is built on top of IBM/Semtech Lmic v1.6 [16]. This software is enabling almost bare metal access to the radio and therefore allows for better control and flexibility. The LoRa frames were 59 B long with random payload, including an implicit header and a CRC checksum. The time gap between packets here was 576 µ sec. The time on air is a variable in LoRa that changes when we use different configurations, i.e., it depends on the used SF and BW values. The CR we used was always 4/5.

Both radios transmission power were 14 dBm. In order to measure the consumed energy, we used a logic analyzer and an oscilloscope to measure the precise time and energy consumption of transmitting a frame and running the CCA mechanism. For visualizing of Wi-SUN and LoRa frames, we used a Software Defined Radio (SDR) module.

The following scenario is used throughout the evaluation. To ensure that
we always have interference when the transmissions overlap in frequency, the LoRa node transmits frames as continuously as possible.

To obtain a variety of none, partial, and full overlap in terms of frequency, we set the Wi-SUN in a fixed channel and vary the LoRa central frequency. At the beginning of this experiment, the central frequency of LoRa had an offset of $-500$ kHz to the Wi-SUN receiver. Then, we changed the LoRa central frequency in steps of $10$ kHz whilst the Wi-SUN channel remained fixed.

To explore a range of LoRa modulation parameters, we used four combinations of bandwidth and spreading factor values.

The goal was to capture several cases which will evaluate the mechanisms under different conditions. Approximately 48% of the scenarios had no frequency overlap between the LoRa and Wi-SUN channels, while 52% had partial or complete overlap.

### 4.1 Detection of LoRa signals

In this part we analyze the ability of a Wi-SUN network to detect LoRa signals with ED measurements based on the RSSI function of the hardware. The Wi-SUN receiver is sampling 400 ED values, one each 10 msec. Each ED sample is an average of the energy in the channel during $21.3\mu$sec. We repeat the same scenario for different LoRa settings. The Wi-SUN transmitter is not used in this experiment.

Fig. 2 depicts the results. The gray background represents the fixed channel used by default Wi-SUN and every point in the figure, the average value over the sampled ED values or the noise floor. Every curve here represents how Wi-SUN is able to identify LoRa for a given LoRa configuration. An observation here is when the offset of LoRa is $\pm100$ kHz, we expect the ED level to be around $-22$ dBm, because LoRa transmitting power is 14 dBm and the attenuator is 36 dB. This is happening because LoRa is spreading the energy along its BW which is 125 or 500 kHz in this experiment. In order to be captured, the Wi-SUN node needs a similar filter BW and both of them need to use the same central frequency. Otherwise there is a partial capture which does not represent the overall signal power. Another thing we see is that even when LoRa is transmitting in the used channel, the standard deviation, represented with the error bars, is large. Capturing an ED sample value which indicates that LoRa is present is important because this value is going to answer if the channel is busy or not.

Fig. 3 illustrates three examples from Fig. 2, namely, the LoRa configuration of SF7 and BW 125 kHz. We can clearly see that the average RSSI value does not give all the information required. In Fig. 3a, LoRa central frequency is exactly at the center of the channel used by Wi-SUN. However,
the LoRa transmission is using a larger bandwidth (125 kHz) than Wi-SUN (98 kHz). This means that sometimes, the LoRa chirp is partly outside the detection band and that leads to a lower ED sample as the sample is an average of the time slot. In Fig. 3b and Fig. 3c, this becomes even more apparent as the channels only partly overlap due to the central frequency offset, with the latter only overlapping by 12.5 kHz (excluding adjacent-channel interference).

4.2 Interference of LoRa signals

The next thing we need to understand is how Wi-SUN and LoRa transmissions collide when the two radios operating frequency overlap partially or completely. The scenario for this step, which is based on the setup of Fig. 1, is that the Wi-SUN transmitter sends the maximum amount of frames possible in 5 sec from a Wi-SUN transmitter to a Wi-SUN receiver in a fixed channel. LoRa, during this time period, act as interferer by sending packets also at the maximum number of frames possible, i.e., all packets collide all the time. Due to the use of RF-combiner, no external interference is present. We changed the LoRa central frequency in the same manner as in the previous scenario to evaluate how the interference is in the same channel, but also in the adjacent ones. No CCA mechanism was used in these experiments in order to obtain the ground truth and to be used as point of reference in the evaluation in Section 6.

In [1] we carried out an experimental evaluation between Wi-SUN and LoRa in an anechoic chamber following a similar scenario. In that work, we investigated how much these networks affect each other when they co-exist without any MAC or collision mechanism used. We were able to quantify the degree of interference that can be tolerated from both networks and point out which factors are important. We follow an analogous approach to capture how much damage LoRa can cause to Wi-SUN with the CCA mechanism deactivated.

Fig. 4 presents the Wi-SUN Packet Reception Ratio (PRR) while LoRa was interfering with different configurations. When the LoRa bandwidth is 125 kHz and LoRa is in the used channel, the PRR drops to zero as expected. The same behavior is visible when the bandwidth is 500 kHz and the offset is $\pm 300$ kHz. When LoRa has a larger BW, it affects Wi-SUN from a longer offset.

5 Design and Implementation

This section presents the design principles and implementation procedure of our Enhanced CCA mechanism, a mechanism that estimates more accurately
Figure 3: Histograms of Wi-SUN sampling the channel while LoRa is transmitting with SF7 and bandwidth 125 kHz. \( n = 400 \) packets. (a) Offset 0 kHz (b) Offset -50 kHz (c) Offset -100 kHz

whether a channel can be used by Wi-SUN nodes when LoRa is present. Our goal is that Wi-SUN nodes should mitigate the impact of LoRa interference and at the same time improve the energy-efficiency.

The main goal of the Enhanced CCA mechanism is having a more precise detection of surrounding LoRa interference and use that in the CCA procedure. In order to guarantee such a feature, we propose an extended energy scan of the channel every time the CCA is used. In this way, if LoRa interference occurs, the network should be able to predict more efficiently a collision. Moreover, in this way less energy is wasted which is important for the lifetime of the node. This mechanism is designed to be efficient against LoRa interference. The modulation of LoRa is making its transmissions in a very specific and unique manner because the signals are chirps going upward or downward of the bandwidth. Hence, another co-existing frame at the same time in the spectrum is difficult to be delivered uncorrupted. To this end we propose that a more accurate representation of the channel energy will reduce the number of the collisions.

Algorithm 1 Enhanced CCA

1: procedure Get channel status
2: \( m \leftarrow -124 \) dBm, \( SampleCounter \leftarrow 0 \)
3: while \( SampleCounter < Nsamples \) do
4: \( m \leftarrow \text{MAX}(m, \text{GetRSSISample}()) \)
5: \( SampleCounter++ \)
6: if \( m + \kappa > \text{CCAThreshold} \) then
7: \( \text{return BUSY} \)
8: \( \text{return IDLE} \)

Algorithm 1 describes the design of the Enhanced CCA with pseudo code.
Low-Power IoT radio devices are vulnerable to noise, that is why getting a larger amount of ED samples is important. This helps the algorithm to identify more precise if there is an interfering signal in the channel and how powerful it is. Therefore, the first step is to get the ED samples and then select the maximum among them. Then we add the constant $\kappa$ to the maximum ED sample, which is the co-channel rejection ratio of the used radio. Low-power radios are able to receive a frame successfully only if the signal is higher than the noise and interference by the amount defined by the co-channel rejection. The final value is returned and compared against the defined threshold of CCA.

The Enhanced CCA implementation is based on the version implemented in Contiki-OS [12] for the CC1310 launchpad [11] used in the proprietary mode. The constant $\kappa$ is indicated in the datasheet [11]. We did not use the Contiki MAC or any duty cycle in order to ensure the minimum time gap between frame transmissions. In this way we enforced more collisions during the experimental evaluation and tested the efficiency of the mechanisms. The number of ED samples used in the experiments for the Enhanced CCA was 50, the number was defined empirically. The duration of sampling one ED value is $21.3 \mu\text{sec}$ and the minimum time interval for sampling again is $1.3 \mu\text{sec}$. Thus, the overall time for getting 50 samples is $1.11 \text{msec}$.

This sample time is considerably longer than the 0.160 msec time used by the default CCA. We must therefore consider how this change affects the existing CSMA backoff procedure. In the IEEE 802.15.4 standard, the random backoff duration is always an integer multiple of the unit backoff period, whose duration is the sum of the sample time and the radio turn-around (rx-to-tx) time. For the sub-GHz radio, these values are 0.160 msec and 1.0 msec respectively, for a total of 1.16 msec. Using this definition directly would increase the unit backoff period to 2.1 msec, which would require a significant change to the standard. However, we note that the enhanced CCA duration is slightly less than the standard unit backoff period. As long as the random backoff interval is at least two unit backoff periods long, part of the backoff interval can be used for the enhanced CCA without significantly changing its externally visible behavior.

We compare the Enhanced CCA with the CCA mechanism stipulated in the IEEE 802.15.4 standard. The IEEE 802.15.4 standard stipulates a CCA period of 8 symbol periods, which is 170.4 $\mu$s, and calculating the average detected energy. Hence, we collect 8 ED samples in the proprietary mode in quick succession and calculate the arithmetic mean. If this value is higher than a given threshold (usually $-90 \text{dBm}$), the channel is deemed busy, otherwise clear. In this paper, we refer to this mechanism as Default CCA. We should also note that a typical time duration of a chirp in LoRa is $2 - 8 \mu\text{sec}$. Hence, even the shortest ED sample duration should be able
Figure 4: PRR of Wi-SUN without the CCA mechanism activated, using the channel mentioned with gray background while LoRa is shifting across the span and act as interferer.

to detect several chirps even when the used channels only partly overlaps.

6 Evaluation

This section reports our systematic measurement investigation including an accuracy analysis, how both CCA versions perform under different LoRa settings and an energy efficiency evaluation.

6.1 Evaluating the effectiveness of CCA

In the first experiment, we compare the two different CCA methods that we have discussed above. We used the setup in Fig. 1, executing the scenario described in the Section 4.2.

All the configuration for either Wi-SUN or LoRa are the same with the previous scenario, the only difference is the following. Before the Wi-SUN transmitter actually transmits, it carries out a CCA and notes down the outcome. In either case, it transmits a packet to see if it collides or is transmitted successfully. The goal is that the CCA outcome will be idle when a transmission is successful and deemed busy when the transmission is unsuccessful. On the one hand, we want a CCA that prohibits transmissions when there is another transmission (a LoRa transmission in our experiment), but also not unnecessarily prohibiting too many transmissions as it will create unnecessary backoffs and delays.

Table 1 summarizes the results. For each transmission, it shows the CCA decision and whether or not the transmission was successful (recall that the frame is transmitted regardless of the CCA decision). The results show that the default CCA correctly identifies essentially all (98%) of the cases in which the transmission will be successful. But when the CCA advises
that the channel is clear, a transmission results in a loss due to collision 24% of the time. Overall, in situations where the transmission will result in a collision, the default CCA correctly identifies the channel as busy only 53% of time not much better than flipping a coin.

The enhanced CCA demonstrates a significantly higher ability to correctly identify a busy channel it does so 79% of the time. When the CCA advises that the channel is clear, a transmission results in loss due to collision only 13% of the time an reduction of over 40%. But this improvement comes at the cost of a more conservative CCA decision: It is possible to successfully transmit in 13% of the cases where the CCA advises that the channel is busy, resulting in a missed transmission opportunity. With the default CCA, this error occurs only 2% of the time. However, the cost of a loss due to collision is much higher than that of a missed transmission opportunity.

In the case of a collision, the sender spends time and energy transmitting the lost frame. If the sender expects and does not receive an ACK, it must also spend time and energy waiting for an inter-frame space, performing backoff and CCA again and re-transmitting the frame. If the frame does not use ACKs, it is simply lost, which has consequences for the performance of higher layer protocols. In addition, the transmission adds noise to the channel while it is already in use, potentially affecting other transmissions.

By contrast, a missed transmission opportunity simply means that the sender performs another backoff and CCA, incrementing the backoff exponent as defined in the IEEE 802.15.4 specification. While this does cost some time and energy, the cost is much lower and other users of the channel are not affected. The frame would be lost (i.e. dropped by the sender) only in the case of several consecutive missed transmission opportunities.

Table 1: Results of CCA experiments

<table>
<thead>
<tr>
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<th>TX OK</th>
<th>TX Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default CCA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCA IDLE</td>
<td>55548(98.5%)</td>
<td>17973(47.6%)</td>
</tr>
<tr>
<td>CCA BUSY</td>
<td>830(1.5%)</td>
<td>19781(52.4%)</td>
</tr>
<tr>
<td>Enhanced CCA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCA IDLE</td>
<td>47094(87.0%)</td>
<td>7484(20.8%)</td>
</tr>
<tr>
<td>CCA BUSY</td>
<td>7016(13.0%)</td>
<td>28498(79.2%)</td>
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Figures 5 and 6 breaks down the results for various LoRa configurations and shows them as a confusion matrix. The metrics are defined as fol-
True Positive (TP) is when there was a collision and CCA marked the channel as busy. False Positive (FP) is when a collision occurred and CCA indicated the channel as idle. True Negative (TN) is the case that no collision occurred and CCA marked the channel as idle and False Negative (FN) is when the channel no collision occurred but CCA indicated the channel as busy.

Figs. 5 and 6 illustrates how the TP and FP are improved. The proposed design is able to predict these cases more accurately because of the extended sampling and selecting the MAX ED sample. However the TN and FN metrics are better in the Default CCA. This is partly explained from the fact that selecting the MAX ED sample is preventing some cases that a proper transmission could have been achieved. An interesting observation here is how these metrics change when LoRa interferes with different settings. The SF and BW in LoRa are affecting several communication metrics. This is why we see different performance when we change these settings. A detailed explanation follows in the next part.

Figure 5: Confusion Matrix statistics for Default CCA throughout different LoRa Configurations

Figure 6: Confusion Matrix statistics for CCA Enhanced throughout different LoRa Configurations
6.2 LoRa Parameters Impact

An observation we can make from Table 1 is that the Enhanced CCA is performing better when LoRa is using lower SF value. We believe that the explanation here is twofold. First, when the SF is lower, the time on air decreases so there are more time gaps between the frames available for Wi-SUN transmissions. The second has to do with the principles of CSS modulation. When the SF and BW values are changing, the angle of the chirp is changing as well. More specifically when the SF is lower, the chirps are becoming more vertical to the overlapping region with the GFSK signals that Wi-SUN uses. Even though that the chirps crosses this region faster than it would with a higher SF value, they also cross this region more often and due to the vertical angle, they are located closer to that part. We believe that these two reasons in combination with the extended ED sampling is making LoRa signals with higher SF value be detected easier from Enhanced CCA. You can see this phenomenon illustrated in Figs. 7 and 8. The signal in the middle of the figures is the Wi-SUN frames and the chirps are crossing the spectrum diagonally with very different angles as we change the SF value.

![Figure 7: LoRa with SF7 and BW 500 kHz and Wi-SUN captured with SDR for 7 msec. The x-axis represents time and y-axis the frequency.](image)

6.3 Energy Efficiency

Since we know from the previous parts that we can avoid some of the collisions by using our Enhanced CCA, we should now see how this affects the energy efficiency. The scenario and configuration we use is the same as before. Due to more correct predictions by the enhanced CCA, we expect fewer collisions at the cost of longer delay. These observations lead us to examine the energy consumption of the two mechanisms. In the following work we quantify the energy consumption, but leave the delay for future
work. In practice LoRa transmission will be sparse due to the regulatory rules regarding the maximum allowed duty cycle.

The expected energy consumption for successfully deliver one frame, $E[e_{fr}]$, can be modeled as a geometric distribution based on the results of Table 1. To do this, we assume a MAC protocol where energy is only consumed during the CCA period (e.g., a MAC based on non-persistent CSMA). We assume the radio can be turned off during backoffs and ignore the energy spent to turn on and off the radio.

Considering the four possible outcomes of Table 1, we realize that only the true positive-case (top left box) leads to a successful frame delivery, the remaining cases either lead to a back-off or a collision. Based on the definition of expected value and assuming $k$ failed frame delivery events, we can find the expected energy consumption as follows:

$$E[e_{fr}] = \sum_{k=0}^{\infty} (1-p)^k \cdot p \cdot (e_{CCA} + e_{TX} + k \cdot E[e_{fail}])$$

$$E[e_{fail}] = q \cdot (e_{CCA} + e_{TX}) + (1-q) \cdot e_{CCA}$$

where $p$ is the probability that CCA predicts idle and the transmission is successful (the true positive case), i.e., $p = TP/(TP+TN+FP+FN)$. $e_{fail}$ is the energy spent on one failed frame delivery and can be further divided into two cases, either we do an CCA scan and it concludes the channel to be idle and we transmit a frame that collides, or we only do an CCA scan that predicts busy. $q$ is the probability that the CCA predicts idle when a transmission is not going to be successful, i.e., $q = FP/(TN+FP+FN)$. The probability of the second case is $1-q$. 

Figure 8: LoRa with SF12 and BW 500 kHz and Wi-SUN captured with SDR for 7 msec. The x-axis represents time and y-axis the frequency.
Eq. (1) can be simplified by using the geometric and the arithmetic-geometric series. We then obtain the following closed-form formula, which we can use to compute the energy consumption:

\[
E[e_{fr}] = e_{CCA} + e_{TX} + \frac{1 - p}{p} \cdot E[e_{fail}]
\]  

(2)

Based on energy consumption measurements, we found that for CC1310, \(e_{TX} = 731 \, \mu J\) and \(e_{CCA} = 8 \cdot 0.54272 \, \mu J\) for the default CCA or \(e_{CCA} = 50 \cdot 0.54272 \, \mu J\) for the enhanced CCA version. Using the values of Table 1, we can find the \(p\) and \(q\) and calculate the expected energy consumption for one frame delivery. For the default CCA, it is \(E[e_{fr}] = 975 \, \mu J\) and for the enhanced CCA version, it is \(E[e_{fr}] = 899 \, \mu J\). Hence, we can conclude a 7.8 % energy reduction.

In Fig. 9, we can see how the energy consumption changes between the two different mechanisms for a few different LoRa configurations. Even though we run the CCA longer, each time we send a message, the energy consumption is lower with the Enhanced CCA. A frame that collides costs more energy overall than running a more precise CCA method. We can also see that the degree of improvement is different for different LoRa parameters. For instance, the improvement when the LoRa parameters are SF12 and BW 500 kHz is 51.76% less energy, but for the case with SF12 BW 125 kHz, it is only 5.94% less energy. This is expected if we take into account that the amount collisions is different for different LoRa settings and this is caused by LoRa’s modulation as we explained in the previous subsection and depicted in Fig. 7 and Fig. 8.

Figure 9: Consumed energy of Wi-SUN frame delivery for different LoRa scenarios and for both the default and enhanced CCA mechanisms.

6.4 Wi-SUN interference

We also compare the two CCA mechanisms against Wi-SUN interference in the following scenario: We used three Wi-SUN nodes in the same channel.
with the same transmission power (14 dBm). A transmitter, a receiver, and an interferer. The receiver and the transmitter were communicating similar as the previous scenario for 5 sec and the interferer was disturbing the communication with 59 B long frames every 60 msec. In this scenario, we cannot have partial channel overlapping and if the interferer transmits packet as fast as the transmitter we will have almost zero received frames. To this end, we increased the interval between the frames sent from the interferer to have a scenario where some frames are able to be received. The PRR was 91% for both mechanisms Default and Enhanced CCA. Hence, we do not see any major difference for Wi-SUN interference, since the improvement was designed focusing on LoRa.

7 Conclusion

Our work reduces the impact of cross-technology interference between two popular LPWAN technologies, LoRa and IEEE 802.15.4g Wi-SUN. We first characterized and then proposed an enhancement to the default CCA mechanism of IEEE 802.15.4g Wi-SUN that improves its ability to detect interfering LoRa transmissions. The evaluation was carried out in a controlled environment using real hardware and used a scenario that included a variety of LoRa configuration settings. The results show that the default Wi-SUN CCA cannot effectively detect LoRa transmissions. We explain this behavior in terms of LoRa modulation. We proposed an enhanced CCA that can detect almost 80% of interfering LoRa transmissions that would otherwise result in a collision, with only a small increase in spurious detections. The proposed change does not affect detection of other Wi-SUN transmissions and is largely compatible with the existing Wi-SUN CSMA backoff mechanism. We also showed that the proposed CCA reduces the energy consumption by 7.8%.

References


Paper III
Using Software-defined Networking Principles for Wireless Sensor Networks
Using Software-defined Networking Principles for Wireless Sensor Networks

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Abstract

In this paper, we propose an architecture based on software-defined networking (SDN) for wireless sensor networks. Ideas of how to design and make use of the flexibility that SDN offers are presented. We discuss how SDN principles can lead to the use of commodity hardware in a wider range of WSN deployments and then tailor the software only to meet the requirements of the specific deployments and their applications. A few examples are introduced that demonstrate how the architecture can be used for networking, in-network processing, and performance predictions.

1 Introduction

More and more physical objects are becoming smart and connected using ICT. A key concept for this is wireless sensor networks (WSN), which connects smart objects with each other in a local area using low power wireless communications. WSN is an important building block for the future Internet of Things (IoT) vision.

WSNs may be used for many different types of applications and in many different types of environments, such as in residential homes, apartment buildings, large office buildings, industrial plants, outdoor in urban environments as well as rural areas. Applications may be delay-tolerant collection of sensor readings, responsive smart home applications, tracking of mobile objects or persons, and time- and mission-critical operation of industrial plants, to name a few.

For the IoT vision to become true, it is important to keep the costs low and this is mainly achieved through economy of scale in both hardware and software. This means both standardized hardware and software. At the same time, application requirements may force us to tailor every single WSN deployment individually and this can only be achieved by a high degree of
reconfiguration capabilities, something that can be realised by using concepts 
and ideas from software-defined networking (SDN) [1].

The developments in hardware have made reconfiguration possible. The 
TelosB WSN node platform [2], which is the most commonly used in the 
research community, is now 10 years old. Today, for example, ARM and 
its partners have released new energy-efficient micro-controllers, such as the 
ARM Cortex M-series, which is suitable for WSN nodes. Some of these have 
a 32-bit architecture and much more program and code memory as well as 
faster processing capabilities than TelosB. Also the wireless chips have been 
updated. All this enables much more functions in software.

This extra functionality enables a much higher degree of tailoring, but 
also more advanced in-network processing. The latter also provides shorter 
communication paths between sensors, actuators, and the data processing. 
This also leads to more robustness due to less dependence on far away nodes, 
as well as lower delays and less energy consumption due to the minimized 
communication paths.

In this paper, we discuss how SDN concepts can lead to the use of com-
modity hardware in a wider range of IoT and WSN applications and then 
tailor-making using software to meet the requirements of the specific deploy-
ments.

The remainder of this paper is organised as follows. Section 2 intro-
duces the SDN-based architecture for WSNs. In Section 3, we discuss the 
networking aspects of the architecture, while in Section 4, we give some ex-
ample SDN applications. Section 5 contains the related work and Section 6 
concludes the paper.

2 An SDN Architecture for WSN

SDN is a concept developed to meet the demands of more flexibility in the 
networking implementations on Internet routers. In SDN, there is a de-
coupling defined between the control plane and the data plane with Open-
Flow [3] being the currently most successful standard. New network control 
and management solutions can easily be deployed by replacing the control 
plane functionality.

We have to mention that an SDN architecture for WSNs includes chal-
lenes. The WSNs have constrained resources and most of the times are 
battery operated, which means that the available energy should be managed 
efficiently. One of the basic functions in a SDN architecture is the com-
munication between the control and data plane and an increase in the 
communication will increase the energy consumption. Thereby, the energy 
efficiency is one factor that should be considered during the design of the
Figure 1: Overall SDN architecture for a WSN

OpenFlow is based on TCP, which means that the control function could run locally on the router or somewhere else, such as at a central server. Through the interface, the controller application can configure the forwarding tables of the router (or network switch). The task of the controller is to provide a coherent image of the entire network and provide it as one single entity towards the SDN applications. Typical SDN applications could be routing, but also other functions, such as access control and software-based traffic analysis, are possible.

The aim of this paper is to propose a flexible architecture for WSN and IoT systems based on ideas from SDN and where in-network processing is a natural part. Figure 1 shows the overall architecture with the SDN layers indicated. Each WSN node is equipped with a local controller, whose functionality can be as simple as just receiving and executing the commands from the central controller. The central controller communicates over the network with either the used routing protocol if it is running or simple networking principles, such as network-wide flooding [4]. On top of this, message formats between the controller and the WSN nodes must be defined.

On top of the central controller, there are one or more SDN applications. These applications can be related purely to the networking of the WSN, such as topology control and routing. In this architecture, some SDN applications may be directed towards the network operator staff with a user interface, while others are completely automated. SDN applications may use optimization solvers, simulators, specifically made algorithms, or a combination.

Figure 2 shows the functionality on the WSN Nodes. Everything, except potentially some parts of the local controller resides in the infrastructure layer. The main task of the local controller is to setup, reconfigure, and monitor the parts of the software that can be reconfigured. It can do so in two ways. Either it changes parameters in the different functions, such as the central frequency of the radio, the retransmission limit in the MAC layer, modifying entries in the forwarding table, etc., or it installs new code in the different functions that changes the behavior. The latter can be
done by virtual machines (VM), but can also be done with native code and dynamically linked library functions. In this way, not only routing and MAC can be modified by the controller, but there is also flexibility for the neighbour and topology discovery functionality as well as other functions.

In-network processing of sensor data is important for the robustness of applications, energy-efficiency, and the reduction of the delay. An application execution environment is defined that allows application code to be updated over the air that can process sensor data as it is being forwarded by the nodes. For instance, the ProFuN TaskGraph Tool [5] can be used.

With a good code execution environment in place on the WSN nodes, it also becomes possible to distribute the controller function. I.e., it is no longer required to run the controller on a central node. Furthermore, hybrid controller versions can be defined.

In homogenous networks, native binaries and dynamic linking can be used, while massively heterogenous networks may benefit from using byte code and VM technology designed for embedded systems. To solve this, some researchers have proposed to put a virtual machine (VM) on the WSN nodes. In this way, one single byte code binary can be distributed and executed on any node. Examples of VMs developed for WSN nodes include EmbedVM, TakaTuka [6], and Darjeeling [7]. The latter two are Java VMs. Another option is using snapMac [8], an architecture where the MAC protocol and radio firmware are independent. This provide flexibility by doing changes in MAC and evaluate the radio services in an easier way. Contiki OS is another alternative which has good support for over the air programming and dynamic loading. Further, it is also important to have a good run-time monitoring system that, for instance, can deal with application processes running out of hand or debugging.

3 Reconfigurable Networking

With SDN, we have the option to centralize all or some parts of the networking at a more powerful node. For robustness reasons, we may not centralize everything. Instead, MAC, forwarding, and many routing decisions are still likely to be carried out by the individual nodes. However, long-term decisions can be taken by a centralized controller, such as which protocol and what parameters to use. A central controller may also have good knowledge about application requirements, which can be taken into account as well.

The central controller needs to discover the actual topology and the quality of the links. This can be done either by packet trace information or simpler link quality estimation (LQE) for the links of the network. What is best depends on how it is supposed to be used. Hence, even this part should
be reconfigurable. Only when data is needed by an SDN application, the collection of data should be started, since every extra data collection will reduce the network life-time.

A packet trace contains detailed information over how packet losses over a link behaves. This information can be used in a simulator (e.g., [9]) with a technique known as trace-based simulation. The simulator can be used to answer questions, such as which protocol is best or which parameters should be selected. The good thing is that the accuracy between the simulator and the deployment will be very good since the trace is collected from the network under study.

While trace-based simulations can offer very good accuracy, trace data is expensive to collect. Hence, more light-weight alternatives are needed. LQE [10] is used to predict a link’s quality for various reasons, such as transmission power control, rate adaptation, and routing. Many such techniques have been proposed [10] and in general they are designed to be light-weight. The collection of LQE for all links and thereby also the network topology has been discussed by a handful of papers, such as [11–13].

To gather LQE information from all links in the network and model this for use by the SDN applications is not a trivial problem. There are many aspects that need to be looked at and that have implications on the overall performance. Questions to be answered includes: What data to collect and how? Packet reception ratio (PRR), received signal strength (RSS), signal-to-noise ratio (SNR), noise level, chip/bit error rate, etc. How often to sample and collect topology information? How much energy do we consume by doing these measurements? Do we gain by doing it?

Many of the answers depend on how the data is being used. The LQE method may also have to take into account different packet sizes, transmis-
sion powers, and data rates, depending on the underlying wireless technology being used. We need to define light-weight mechanisms for collecting topology information that is still useful. Since this functionality also has to evolve, we need this collection mechanism to also be replaceable. By updating the code, what is collected, how it is processed, and when it is communicated can be changed to meet future requirements.

4 Other SDN Applications

When the topology and link information has been collected, it is time to make use of it. Here, we apply this information in four ways.

4.1 Centralized Networking

If LQE or packet trace information is available at the controller, we can use it for routing or tuning routing parameters. In [13], one approach is attempted for centralized routing. The tuning of parameters based on information about the network has been shown by [8, 11]. In general, simulation or optimization solvers may be used to find the right configuration. The new thing here is that we can also take application needs into account in this process.

4.2 Optimal code deployment

Depending on the topology, where a piece of code is executed may have importance on the network life-time and robustness. If the processing of sensor data is done on one of the intermediate nodes, data does not need to make a detour to be processed. Good data about the network can be used together with a solver to find the optimal assignment [5, 14].

4.3 Predicting a WSN networks behavior and performance

Given the topology information, the used protocols, the application behavior, and everything else, it becomes possible to simulate the actual network at hand and predict its behavior and performance. For instance, what is the actual network life-time likely to be and what protocol is best for this particular network and application? Robustness analysis can also be done by simulating link or node outages. A system could also be envisioned that goes one step longer and suggests the network operator to make alterations to the node deployment, such as move or add nodes, use of other antennas, etc.
4.4 Network life-time prediction

Using good energy consumption models [15] together with collected network data, such as radio propagation information and battery levels, better predictions of the network life-time can be achieved. For the overhearing and collisions, it may also be necessary to collect interference information. Interference can be collected by the WSN nodes in a similar fashion to Jam-Lab [16].

5 Related Work

Early on in the WSN research, it has been noted that some MAC protocols work better in some scenarios and other protocols in other scenarios. Hence, reconfigurable or adaptive MAC platform have been proposed. T-MAC [17] is one such early protocol where the listening period is adaptive. C-MAC [18] is a much more recent protocol where many parameters can be reconfigured by the applications. In pTunes [11], the authors treat the parameters of a MAC protocol as an optimization problem. They collect data from the network at the base station where a solver is used to find the optimal parameter configuration. The network is then reconfigured accordingly. With snapMac [8], it is possible to program the radio layer with a sequence (called chain) of simple commands. The idea is similar to a VM with an extensible set of very low-level instructions.

IMPERIA [13] is a centralized architecture for WSNs with data gathering applications. It defines MAC, routing, and management protocols. Its main idea is to move functionality from the simple WSN nodes to the sink (i.e., the controller functionality) in a similar way to a SDN. However, the flexibility of the SDN concept is not at all studied.

Actually using SDN in WSNs has also been studied. Mahmud et al. [19] propose to deploy OpenFlow in WSNs, but the results are limited. The same holds for Luo et al. [20]. In [12], Costanzo et al. propose an architecture for a SDN-based WSN where forwarding tables and in-network aggregation of sensor data can be configured. A method for collecting topology information and configuration packets are proposed.

Software-defined radio (SDR) is another related area where radio hardware is replaced with software or reprogrammable hardware (e.g., FPGA) for increased flexibility. The required intensive signal processing is very energy costly [21] and might not be an option for WSN nodes in the foreseeable future.
6 Conclusions

In this paper, we have proposed a SDN-based architecture for flexible reconfiguration of WSN networking and in-network processing functionality. SDN is an important building block to be able to use standardised low-cost off-the-shelf hardware and yet achieve customization suitable to the individual deployments. We have discussed how the architecture can be used for different purposes, including networking, in-network processing, and WSN management tasks.

An important step in validating the architecture is to implement a prototype version of it. In the future, we aim to make such a prototype and demonstrate its flexibility by implementing multiple controllers and SDN applications on common WSN hardware for different types of applications, such as data collection applications as well as sense-compute-act type of applications.

An interesting research question raised here is the investigation of the tradeoff between SDN applications and their energy efficiency. In the future work it would be interesting to evaluate in terms of energy efficiency, SDN applications such as routing, access control etc in comparison with regular applications in order to provide a complete image of performance.

Acknowledgments

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References


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<td>2016-006</td>
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