Robust Low-Power Wide Area Networks for Sports and Health

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Doctoral thesis

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Abstract

Low-Power Wide Area Networks (LPWANs) has enriched the IoT ecosystem with new features and application scenarios. LPWANs offer long range communication and can be used to connect devices that are divided by long distances and offer connectivity to remote areas where cellular networks are not accessible. They utilize their long range, low-power robust communication to enable popular application scenarios, such as smart cities and smart agriculture.

However, the environment that most of these networks operate in is unlicensed spectrum, which might be crowded and noisy due to the co-existence of other networks and technologies that operate in the same frequency band. Therefore, one of the goals of this thesis is to investigate the degree of robustness in LPWANs and propose seamless mechanisms that ensure robust communication in case of high degree of interference. Another goal is to support application scenarios in sports technology and health, which require robust and long-range communication. Hence, the second goal of this thesis is to explore how to take advantage of the robust communication that LPWANs offer, and use it in application scenarios in sports technology and health.

To realize the aforementioned goals, this thesis is quantifying the tolerance level of LPWANs in high interference level environments and suggests methods that will make the co-existence of these networks more sustainable. It also demonstrates that LPWANs can be used in healthcare and safety contexts with a use case of a long-range emergency system. Finally, this thesis provides evidence that LPWAN is a good fit for sports technology applications as it presents a use case where long range time synchronization is offered for a kayak training application using LPWAN.

Sammanfattning

Energisnåla långdistansnätverk, på engelska Low-Power Wide Area Networks (LPWAN), har berikat IoT-ekosystemet med nya funktioner och möjliga tillämpningsområden. LPWAN erbjuder trådlös kommunikation med lång räckvidd och kan användas för att ansluta apparater som är långt ifrån varandra samt erbjuder uppkoppling till avlägsna områden där mobilnätet inte är tillgängligt. De använder sin långa räckvidd, låga strömförbrukning, och robusta kommunikation till att möjliggöra populära tillämpningsområden, så som smarta städer och smart jordbruk.

Dock använder de flesta av dessa nätverk olicensierat spektrum, vilket kan vara trångt och fullt med andra nätverk och tekniker som använder samma frekvensband. Därför är ett av målen med denna avhandling att undersöka graden av robusthet hos LPWANs och föreslå smidiga mekanismer som säkerställer robust kommunikation även vid stora störningar från andra nätverk. Ett annat mål är att stödja applikationsscenarier inom sportteknologi och hälsa, vilka kräver robust kommunikation med lång räckvidd. Därför är det andra målet med denna avhandling att utforska hur man kan dra nytta av den robusta kommunikationen som LPWAN erbjuder och använda den i tillämpningar inom idrottsteknologi och hälsa.

För att möta de ovannämnda målen, så börjar denna avhandling med att kvantifiera toleransnivån hos LPWAN när de använder spektrum med mycket interferens, för att sedan föreslå nya metoder som gör samverkan mellan dessa nätverk mer hållbar. Avhandlingen visar också att LPWAN kan användas i hälso- och säkerhetssammanhang med ett användarfall på ett personlarmsystem med lång räckvidd. Slutligen ger denna avhandling bevis på att LPWAN passar bra till applikationer inom sportteknologi eftersom ett användarfall presenteras där tidssynkronisering över långa avstånd implementerats i ett kajakträningsprogram med hjälp av LPWAN.

Acknowlegments

Obtaining a PhD degree is a very long and difficult journey but I was lucky to meet several people that helped me throughout. First, I would like to thank my supervisor Martin Jacobsson for giving me the opportunity and freedom to work on topics I liked. That was one of the parts that I really enjoyed during my PhD. Second, I would also like to thank Xenofon Fafoutis for our long collaboration, the opportunities he gave me to work with him and for being my co-supervisor. Furthermore, I would also like to thank Per Gunningberg for being my co-supervisor.

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List of appended papers

Paper A

C. Orfanidis, L. M. Feeney, M. Jacobsson, P. Gunningberg. Investigating interference between LoRa and IEEE 802.15.4g networks. *In Proceedings of the 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Rome, 2017*

Paper B

C. Orfanidis, L. M. Feeney, M. Jacobsson, P. Gunningberg. Cross-technology Clear Channel Assessment for Low-Power Wide Area Networks. *In proceedings of the 16th IEEE International Conference on Mobile Ad-Hoc and Smart Systems (MASS), Monterey, CA, 2019*

Paper C

C. Orfanidis, R. B. Hassen, A. Kwiek, M. Jacobsson. Intelligent Foot Gesture Interface for Resource-Constrained IoT Devices. *Submitted to international conference*

Paper D

C. Orfanidis, L. Remahl, X. Fafoutis, J. Wåhslén, H. Rosdahl, J. Nilsson, M. Jacobsson. Synchronization over Long Range: A kayak training scenario. *Submitted to international journal*

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List of papers not included in this thesis

In addition to the papers that this thesis is based on, I have authored or coauthored the following peer-reviewed papers, posters and demonstration abstracts as a PhD student.

- M. Haubro, C. Orfanidis, G. Oikonomou, and X. Fafoutis. TSCH-over-LoRa: Long Range and Reliable IPv6 Multi-hop Networks for the Internet of Things. In: *Internet Technology Letters, April 2020*
- C. Orfanidis, K. Dimitrakopoulos, X. Fafoutis, M. Jacobsson. Towards Battery-Free LPWAN Wearables. In: *(Demo) Proceedings of the 7th International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems (ENSsys), New York, NY, 2019*
- L. M. Feeney, C. Orfanidis, M. Jacobsson, P. Gunningberg. Preliminary results on LoRaWAN and IEEE 802.15.4-SUN Interference. In: *(Poster) Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems (SenSys), Shenzhen, China, 2018*
- C. Orfanidis, L. M. Feeney, M. Jacobsson. Measuring PHY layer interactions between LoRa and IEEE 802.15.4g networks In:*(Poster) IFIP Networking 2017, Stockholm*
- C. Orfanidis. Increasing Robustness in WSN using Software Defined Network Architecture. In:*(Poster) PhD forum at the 15th ACM/IEEE Conference on Information Processing in Sensor Networks (IPSN 2016), April 2016, Vienna*
- X. Fafoutis, A. Di Mauro, C. Orfanidis, N. Dragoni. Energy-Efficient Medium Access Control for Energy Harvesting Communications. In: *IEEE Transactions on Consumer Electronics, 61(4): 402-410, 2015*
- C. Orfanidis, Y. Zhang, N. Dragoni. Fault Detection in WSNs - An Energy Efficiency Perspective Towards Human-Centric WSNs. In: *Proceedings of the 9th International KES Conference on Agents and Multi-Agent Systems: Technologies and Applications (KES-AMSTA'15, session on Anthropic-Oriented Computing), 2015, Springer*
- M. Jacobsson, C. Orfanidis. Using Software-defined Networking Principles for Wireless Sensor Networks. In: *The 11th Swedish National Computer Networking Workshop (SNCNW'15), Karlstad, Sweden, May 28-29, 2015*

- H.-J. Enemark, Y. Zhang, N. Dragoni, C. Orfanidis. Energy-Efficient Fault-Tolerant Dynamic Event Region Detection in Wireless Sensor Networks. In: *Proceedings of IEEE VTC Workshop on Heterogeneous Networking for the Internet of Things, 2015, IEEE*

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List Of Acronyms

BER	Bit Error Rate
BLE	Bluetooth Low Energy
BW	Bandwidth
CCA	Clear Channel Assessment
CSS	Chirp Spread Spectrum
CTI	Cross Technology Interference
EH	Energy Harvesting
EMG	Electromyography
FER	Frame Error Rate
GFSK	Gaussian Frequency Shift Keying
HCI	Human Computer Interaction
IoT	Internet of Things
ISM	Industrial Scientific Medical
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
NB-IoT	Narrowband IoT
MAC	Medium Access Control
MCU	Micro controller Unit
ML	Machine Learning
MLP	Multi Layer Perceptron
NN	Neural Network
PCB	Printed Circuit Board
PRR	Packet Reception Ratio
SER	Symbol Error Rate
SF	Spreading Factor
SNIR	Signal to Noise plus Interference Ratio
SVM	Support Vector Machine
TSCH	Time Slotted Channel Hopping
Wi-SUN	Wireless Smart Utility Network

Chapter 1

Introduction

Low Power Wide Area Networks (LPWANs) emerged the last decade and held the promise to enrich the Internet of Things (IoT) with a missing feature, long range communication with low energy consumption. This premise enabled: connectivity between networks divided due to communication range limitations, coverage to remote areas where they were not covered by cellular networks and new application scenarios that can utilize long range communication, such as smart cities [1, 2], smart agriculture [3, 4]. One of the challenges comes with the fact that LPWANs are increasing in popularity, is the level of Cross Technology Interference (CTI) between LPWANs and other existing technologies in the same bands.

The new features that are coming along with LPWANs may contribute to several application scenarios. This thesis focus more on health and sport applications. There are plenty of examples where long range coverage, robust and reliable communication features are required to implement health applications such as: wearables to track kids and elderly [5], Alzheimer patient tracking [6], offering healthcare and monitor patients remotely [7]. Likewise robustness and long range communication may be required in sport applications in scenarios such as long range tracking in ski [8], activity monitoring and recognition in long range [9]. The main challenge in most of the aforementioned examples is that these scenarios used to require higher bitrate and channel utilization in the past but with LPWANs they have to comply to more limiting channel regulations and lower bitrate.

1.1 Contributions

The contribution of this thesis expands on three main fields, Mobile Communications, Human-Computer Interaction (HCI) and Ubiquitous Computing as it it is illustrated in Figure 1.1.

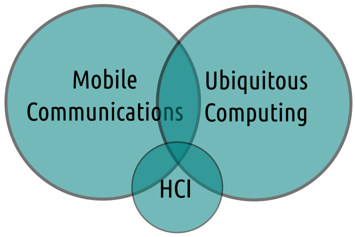


Figure 1.1: The contribution of this thesis lies upon the intersection of these fields

This thesis is constructed around four papers and their research questions accordingly. Therefore the contributions are summed up as follows:

- Emerging LPWAN technologies, such as LoRa and IEEE 802.15.4g Wi-SUN, and their co-existence in smart cities will result in high levels of CTI. Quantifying the CTI levels by carrying out a systematic methodology using highly controlled experiments, allowed us to to put in perspective the level of CTI tolerance between the investigated technologies.

- The evaluation of IEEE 802.15.4 Clear Channel Assessment (CCA) mechanism under LoRa interference with hardware experiments was illustrated to have an inadequate performance. We propose an enhanced CCA mechanism based on a Multi-Layer Perceptron classifier. The enhanced CCA was demonstrated to reduce the dropped transmissions to a large degree and at the same time remaining compatible with the IEEE 802.15.4 standard.

- The combination of an LPWAN with a foot gesture interface enabled us to develop a shoe prototype which can be used in various use case scenarios such in Health and Safety, Sports Technology, etc. We focused on an emergency system scenario where the user might feel threatened by a possible perpetrator and is willing to transmit an alarm signal in discreet. Thus, we developed a classifier which ensures that it will be able to distinguish accurately foot gestures from other activities and transmit an alarm message in case of emergency in a smart city environment.

- IoT is used widely in sports mostly for monitoring physical activities but there also cases that it can be used during training to improve specific skills and techniques. In this respect, we focus on how K2 (pairs) and K4 (four-person crews) kayak training can be improved

> by using a system based on IoT. The proposed system is synchronising over long range by combining LPWAN and BLE in order to assist kayak training. We introduced a dual radio platform and a synchronization scheme which we evaluated it under real experiments and a simulation that represents a kayak training.

During the remaining part of this chapter we introduce background concepts that are useful for the reader in order to follow the flow of this thesis.

1.2 Robustness

The property of robustness in computer systems offers stability to a system in order to perform in an expected manner according to the design principles, even for cases where the conditions (environmental, energy) which it was designed for, vary to a certain level. One may misinterpret robustness with reliability which according to [10] is the probability that the hardware, software and firmware of system, will complete a task successfully in a certain amount of time in a specific environment. The difference between the two properties can be clarified with an example considering a radio that is reliable but not robust on high temperature. In that case the radio is not supposed to operate properly under high temperatures. To offer robustness in a system the system itself has to be evaluated under several variations of a condition that might degrade its performance or even make it not functional. The design of the system should be carried out in a way that the system becomes tolerant to a certain level of a varied condition, possibly with some impact to the performance. In this thesis, we focus on quantifying the robustness of LPWANs under CTI and propose a mechanism which can increase it.

1.3 Low power wide area networks

LPWAN can be briefly described as a wireless networking technology which can achieve long range coverage and at the same time keep the energy consumption low, in a level that can be operated by a small battery for many years [11]. There are several LPWAN platforms at the moment, like LoRa [12], Sigfox [13], IEEE 802.15.4g Wi-SUN [14], NB-IoT [15] and beside the long range feature, most of them offer low-bitrate but also robustness and reliability. LPWAN enriched the IoT ecosystem with new offered features that resulted in several new application scenarios but in order to be integrated, there are numerous challenges to be solved. Some of the challenges that this thesis focus on are the following:

- co-existence issues between LPWAN technologies
- the combination of LPWAN and Human Computer Interaction (HCI) challenges in health and sports applications
- clock synchronization over long range for sport applications

1.4 Cross technology interference

The Industrial Scientific Medical band (ISM) is a radio spectrum used by a large amount of applications. There are some characteristics that make ISM enticing like the fact that you don't need any administration overhead to use it. In that sense, it makes it cheaper and more simple to use a frequency band in ISM. This is the main reason why ISM is overcrowded and have become so popular in IoT during the last years. There are several technologies co-existing within the same environment and when they use the same frequency band their transmitted packets might collide and result in a significant performance drop. This phenomenon can be described as Cross Technology Interference (CTI) and has been investigated a lot at the 2.4 GHz band [16, 17, 18]. The LPWANs are different in many contexts (topology, modulation, range coverage, bitrate) from the traditional sensor networks using the 2.4 GHz band and in addition, the frequency band that is used by LPWANs in EU is 868 MHz band. To this end, we focus on the impact of CTI on emerging LPWAN platforms which have different characteristics between them.

1.5 Health systems

IoT, among other fields, has contributed also to healthcare development with sensing technologies combined with Machine Learning (ML) [19] [20], remote health [21] and many other application scenarios. LPWAN features have enabled new options in healthcare. For instance, due to long range coverage, robust communication and low energy consumption, we can monitor a body sensor network on a campus-like scale with one base station [7]. The application scenario this thesis emphasizes is combining an LPWAN with a foot gesture interface to build an emergency system in a smart city environment. The emergency system is meant to transmit alert messages with discreet foot gestures when the user is under a possible threat, such as an attempted assault.

1.6 Sports technology

Training in sports today is different if we compare it with the way athletes were training 20 years ago. Top clubs, national teams and elite athlete agencies are investing in new technologies and infrastructure designed to monitor the performance, but also improve distinct skills during training sessions [22]. Therefore, there are several research attempts targeting sports technology today. IoT has a dominant role in this research endeavours as wearables [23] with the aid of ML techniques [24] [25] have increased their accuracy in monitoring activities and are established in research but also in industry. This thesis focus on a kayak training case and more specifically on exploring the level of paddling synchronization between kayak athletes in the same kayak (K2 and K4). The main issue with the current approaches for that purpose is that they include interaction with the athletes (to start or control the application) and this might distract them and affect their performance. We take advantage of the long range communication of LPWAN to offer remote control to the application in order to not distract the athletes and we use BLE for short range communication to avoid the rigid duty cycle and low bitrate from LPWAN. In addition, the proposed approach enables synchronization with other remote devices such computer vision monitoring systems to investigate further the paddling technique afterwards. A synchronization scheme and dual radio system is proposed and evaluated for this use case.

1.7 Thesis structure

This thesis is composed of two parts, the first part is a synopsis of the work organized in several chapters. Chapter 2 goes through the research questions raised in each paper, the used method and a brief overview of the results. Chapter 3 mentions the related work. Chapter 4 summarizes the appended papers that establish the main theme of this thesis and finally Chapter 5 mentions the concluding remarks and Future work. The next part illustrates the reprint of four papers that this thesis is based on.

Chapter 2

Research Questions and Contribution

This chapter describes the methodology used to answer the research questions which in turn lead to the contributions of this thesis. The first question answered is regarding the tolerance degree of the two selected LPWANs, LoRa and IEEE 802.15.4g when they co-exist. The next question builds on the evidence found from the first question. It particularly seeks a way to improve the CCA mechanism under LoRa interference after its evaluation proved it to be incapable to handle LoRa interference. The next part is answering how LPWAN can be combined with a foot gesture interface for implementing an emergency notification system on a resource constrained device. The last research question targets on how we can have long range time synchronization using LPWAN, but not be restricted by duty cycle regulations in a shorter range locally. To explore this further, this thesis focus on a kayak training case and an evaluation upon this.

2.1 Methodology

All the research questions have been formulated after following in detail the latest scientific literature and analyzing related research problems. The research methods used in this thesis are mostly based on experimentation using real hardware. These methods were trying to capture cases in real life, repeated covering a wide domain with interventions on specific variables that proved to have a contributing cause to the investigated problem. Controlling adequately the background variables was a requirement to offer a systematic method that was able to capture the desired results, but at the same time eliminate any cases of errors. The vast amount of results gave us insights to draw conclusions and consider future paths of our work.

In order to derive the first part of the contributions, two LPWAN platforms were used, LoRa and IEEE 802.15.4g, in an anechoic chamber to eliminate any source of external interference and establish a highly controlled environment. This enabled us to quantify the tolerance of one radio to the other during CTI. During the next part of our contributions, we used an RF combiner with signal attenuators to have a high degree of control. This setup was used to evaluate and improve the CCA mechanism, included in the IEEE 802.15.4 standard, under LoRa CTI. In both of the methods you can have high control of the environment and conduct a systematic evaluation to answer the research questions. However if one is interested to investigate more the multipath propagation and other phenomena that makes wireless communication challenging, the first method would be more appropriate because these effects do not occur in the RF combiner.

The next contribution presents how feet gesture patterns can be identified with high accuracy by a lightweight Neural Network (NN), implemented on an LPWAN platform. To illustrate this, we developed a prototype which was tested by two individuals using a treadmill for offering higher control, but also an urban environment to offer results closer to a real life scenario. This method included two separate environments of experimentation to show the convergence of the results between them and highlight their validity. Finally, the last part of the contribution presents how you can offer long range time synchronization and at the same time avoid the duty cycle limitations imposed from LPWAN technologies on a short range. To enable these, we propose a simple synchronization scheme and we developed a dual radio platform which included a LoRa and a BLE radio. LoRa was used to synchronize over long range with a gateway and the BLE offered communication on the short range. To evaluate this, we used a logic analyzer where we connected all the nodes we wanted to synchronize and the gateway to check the synchronization error. Since the required synchronization level does not consider for propagation delay, we omitted long range experiments.

2.2 Co-existence in LPWAN

The vision of IoT which includes a plethora of application scenarios, some of them that LPWANs is the key component are smart cities and smart buildings. In order to realize this vision it is required an environment which can ensure reliable and robust operation for the IoT applications. However, the feedback we get today about these environments indicate that the interference generated from several sources will only increase. Moreover, some of the application scenarios offered, include cases among smart healthcare [26], industrial control [27] where high robustness and availability are a necessity. Therefore, we need to ensure that these services and application scenarios will be able to perform properly in an environment with noise and an increasing amount of interfering networks. LPWAN is an enabler for new application scenarios in IoT. Hence, LPWANs are gradually integrated into the IoT ecosystem and it is certain that their number will increase. Another issue is that most of the LPWANs operate in the ISM band, consequently the probability of independent LPWAN co-existing within the same environment and thus using the same frequency is getting common. These networks are heterogeneous in different terms of radios, protocols, channelization, transmission range, etc. In addition these networks may be deployed by different actors generally without coordination. Sometimes, even with potentially conflicting goals. This is exacerbated by the fact that there is currently no coordination mechanisms to deal with these issues among co-located networks. In that case it does not matter if these networks are homogeneous or not. As a consequence, the network traffic in these frequencies might escalate to a level that network co-ordination will become complex due to the heterogeneity, the fact that these networks are independent and operated by different actors and the increased instances of CTI. To this end, we have to acquire insight into the effect of CTI to LPWANs and quantify it to ensure that the promising applications and services offered will function robustly and reliably.

Research Question: The research question we answer here is how tolerant are to CTI LoRa and IEEE 802.15.4g, in terms of PRR when they co-exist within the same environment without using any collision avoidance mechanism. A follow up question we address is which factors may impact this interaction.

Method: We carried out experiments with real hardware and focused on a main scenario with three nodes deployed in an anechoic chamber. The main purpose of the evaluation was to obtain vast amount of results under varying configuration settings, which would help us to answer the raised research question. The main experiment scenario included two nodes (i.e. IEEE 802.15.4g), a transmitter, which was sending frames as fast as possible to a receiver and a third node (i.e. LoRa) sending frames as fast as possible in order to generate CTI and have the role of interferer. We repeat this scenario by changing radio configurations to understand which factors are important and can offer robustness to each LPWAN. Some of the radio configurations we were altering in LoRa is the Spreading Factor (SF), which is the ratio between chip rate and the underlying symbol rate, and the Bandwidth (BW) which is the frequency domain a chirp can go to. This helped us to systematically investigate and quantify the CTI tolerance of both radios to each other.

Evaluation: We use heatmaps to present the results of IEEE 802.15.4g

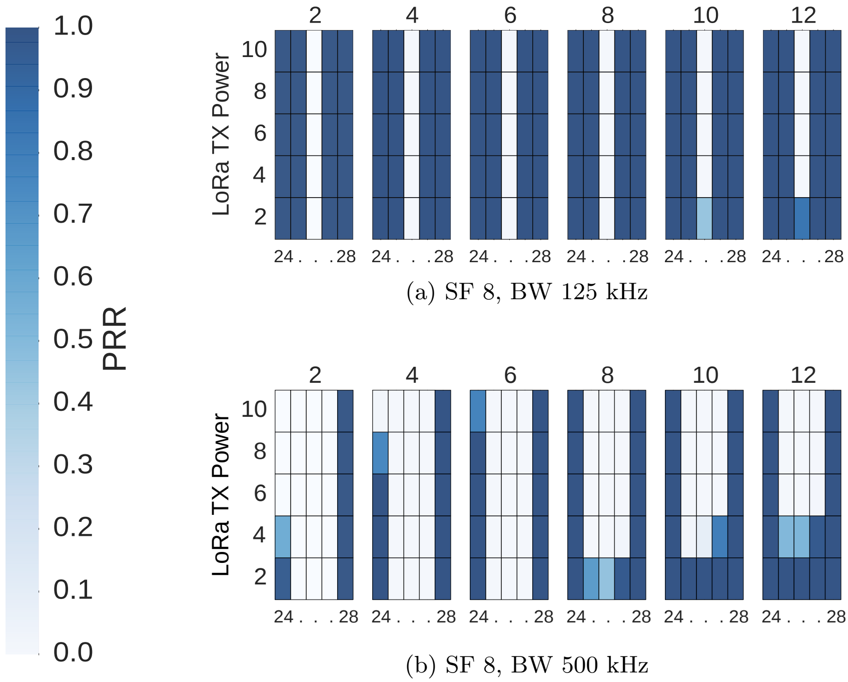


Figure 2.1: Heatmap of IEEE 802.15.4g PRR under LoRa interference. On the bottom x-axis are depicted a set of channels for IEEE 802.15.4g (24-28) which are repeated for each TX power value of IEEE 802.15.4g which are presented at the top of x-axis. On the y-axis is depicted the LoRa interference TX power in dBm. For instance, the leftmost bottom block at subfigure 2.1a 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 8 and the BW 125 kHz.

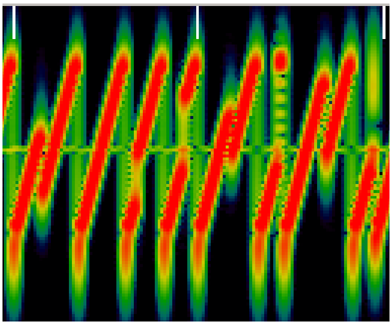
PRR under LoRa interference in Figure 2.1. Every set of block represent a different set of configuration of LoRa (SF and BW). Figure 2.1 illustrates a part of the results. The complete set is presented in Paper A. The PRR is represented by the shade of blue as indicated from the color bar. White stands for 0% and the darkest shade of blue for 100%. Every rectangle in a block represents the PRR of IEEE 802.15.4g using a specific radio channel noted in the bottom x-axis, transmitting with the TX power noted in the top x-axis, while LoRa was interfering in a fixed frequency (868.3 MHz) and using a TX power noted at the y-axis. For example, in Figure 2.1a if we take the lowest rectangle to the left, the PRR is 100 % in an interaction where IEEE 802.15.4g was transmitting at 2 dBm using channel 24 and LoRa was interfering with a TX power at 2 dBm.

An obvious observation is that the BW value of LoRa was responsible for how many IEEE 802.15.4g channels were interfered in this experiment. The IEEE 802.15.4g channels are 200 kHz wide and when the BW value in LoRa is 125 kHz, only one is affected, but if we observe Figure 2.1b where the LoRa BW is 500 kHz, we see that 3 or 4 channels are affected depending on the ratio of the transmission, the interference power and the degree of overlap on each channel. In addition, Figure 2.1 illustrates that when the TX power in IEEE 802.15.4g is increased, the PRR is increased as well. For instance, in Figure 2.1a, when IEEE 802.15.4g is using channel 26 and both radios transmit at 2 dBm, the PRR is 0%, but when the TX power of IEEE 802.15.4g is increased to 12 dBm, the PRR goes to 74%.

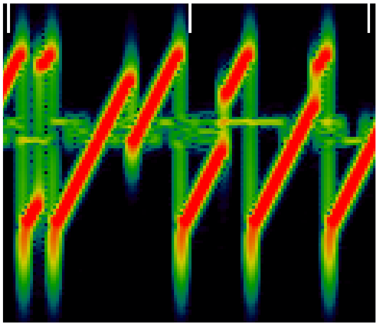
Another observation we did is linked with the physical characteristics of the two collided signals. IEEE 802.15.4g uses Gaussian Frequency Shift Keying (GFSK) modulation where two specific frequencies, within the designated bandwidth, are used to represent 0s and 1s to encode information. LoRa uses Chirp Spread Spectrum modulation where the signals are chirps going upwards or downwards in frequency within the used bandwidth. When the ratio of the transmission powers is in favour of IEEE 802.15.4g and the frequencies between the two signals are partially overlapping, an amount of IEEE 802.15.4g frames are received successfully. We can describe this as a tradeoff between the SF in LoRa and the PRR of IEEE 802.15.4g. We noticed that when we increased the SF value, the PRR of IEEE 802.15.4g suffered a slight drop. We explain this in terms of LoRa's modulation, when the SF increases, the angle of the chirp becomes less steep and there is a higher degree of overlap with the GFSK signal. Figure 2.2 illustrates how the angle of a LoRa single chirp changes as we change the SF value from 7 to 8. We have to mention also that IEEE 802.15.4g is able to tolerate more LoRa CTI when LoRa uses a SF with a lower value because the two signals overlap will last less time.

2.3 Clear channel assessment for LPWAN

The previous part of the co-existence between LoRa and IEEE 802.15.4g networks gave us some evidence on the robustness of the two technologies. IEEE 802.15.4g seems to be less resilient and less robust against CTI. Another motivation to work towards this direction is research such as [28], which reported high levels of interference of LoRa and SigFox networks in the 868 MHz band. The results present levels of over -105 dBm in up to 33% of measurements in specific locations in Aalborg, Denmark during



(a) SF7 BW500 kHz



(b) SF8 BW500 kHz

Figure 2.2: LoRa chirp changing as the SF value is altered captured using a Software Defined Radio. X-axis represents time and y-axis the frequency.

2017. Furthermore, Semtech, the LoRa radio manufacturer, published a report [29] that presents a large-scale deployment of a LoRaWAN network for the purpose of smart metering. They consider an architecture comprised of different type of gateways, long-term bitrate distribution and data loss measurements to generate a model of high-capacity LoRaWAN network. The report underlines the micro-diversity characteristic of the architecture, which will lead to multiple transmissions of frames that will be received by more than one gateway. In the aforementioned scenario, the maximum capacity that can be reached is 63% of channel utilization, which entails that increased level of CTI.

To this end we decided to explore strategies to mitigate interference caused by LoRa and LoRaWAN networks. We focused on the default CCA mechanism described in the IEEE 802.15.4 standard and we combined it with a neural network-based classifier to improve its performance to recognize LoRa interference.

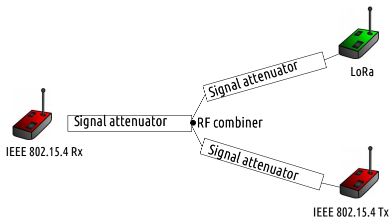
Research Question: The research question raised at this part is on how suitable is the CCA mechanism included in the IEEE 802.15.4 standard to cope with CTI from LoRa networks and how it can be improved?

Method: The chosen method was to use hardware and real experiments again, but instead of using the anechoic chamber, we connected all the interacting nodes with an RF combiner and signal attenuators for practical reasons. Figure 2.3a illustrates the testbed we used. It consisted of three nodes, two IEEE 802.15.4g as transmitter and receiver and a LoRa node as interferer. The wired connection through the RF combiner certifies the absence of external noise and interference and the signal attenuators enable us to regulate the signal intensity for each scenario. Furthermore each node is shielded using a steel container to prevent any signal leakage which could affect the measurements.

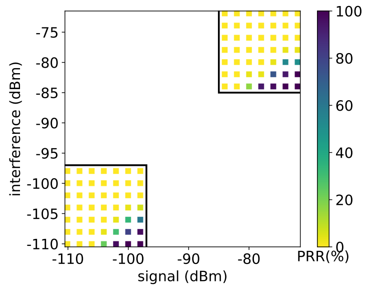
After we had ensured a controlled environment, we did some measurements to see what Signal to Noise plus Interference Ratio (SNIR) is interesting towards our research question. In other words, what is the SNIR domain that a carrier sense mechanism, like CCA can assist on collision avoidance. Figure 2.3b presents the regions we used in our experiments. These regions were selected because the SNIR can affect the PRR and change it from 0% to 100%, thus the selected regions illustrate harsh conditions where utilizing a CCA mechanism can make a difference. There are two regions depicted, one with high received signal strengths and and high interference and one with low received signal strengths and low interference. We excluded cases with high interference and low received signal strength and vice versa due to the reason mentioned above.

Having defined the SNIR regions that makes sense to evaluate and improve CCA on, we followed an ex post facto approach to evaluate the default and improved versions of CCA. Namely, we created a dataset focusing on the regions of interest including more than 646,800 interactions between the two networks. Every interaction is created as follows: While LoRa is interfering as fast as possible, the IEEE 802.15.4g sender is sampling the channel to detect for a duration of 8 symbols (106 usec). Then it sends a frame without consulting the CCA mechanism and record if the frame was received successfully or not. We repeated this scenario and changed several configurations in both networks (channel offsets, LoRa parameters, signal and interference strengths). In this way we were able to evaluate the default CCA and the improvement offline.

Evaluation: Initially we evaluated the accuracy of CCA under LoRa interference. At this point we have to mention that we consider the metric accuracy as defined in a confusion matrix, the ratio between the true decisions to the sum of true and false decisions [30]. Figure 2.4 presents the accuracy with factors that affect it, SF in 2.4a, channel offset in 2.4b, and interference in 2.4c. The default CCA accuracy is 43% in some cases, which is less than a coin flip. The default* is a straw-man CCA, which just samples the channel for a longer time than the default one. Observing the low performance of the default CCA, we decided to implement a NN approach, which will be able to identify LoRa interference more accurately. At the same time we consider the complexity of the implementation, since it is going to operate on Microcontroller Units (MCU) with limited resources. Furthermore, compatibility issues with the IEEE 802.15.4 standard are con-



(a) Experimental setup



(b) Heatmap of dataset

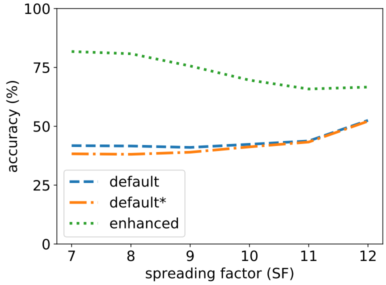
Figure 2.3: Testbed used to acquire the used dataset

sidered. The approach is a Multi Layer Perceptron (MLP) classifier which is trained with 70% of the dataset and the remaining 30 % is used for testing. The enhanced version increases the accuracy up to 73% for some cases and it is illustrated that under the different affecting factors, it is improving the accuracy in most of the examined cases.

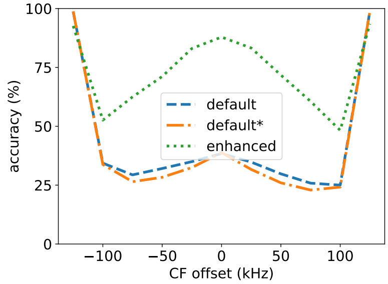
2.4 Foot gesture interface for LPWAN emergency systems

Today we use more and more wearables and mobile devices to perform various tasks in our daily life. The usage of such devices have been established in the IoT ecosystem due to rapid developments in fields like mobile and ubiquitous computing. These developments allowed us to invent new means or improve existing ones to perform tasks related to physical activities such as healthcare and safety [31], and sports technology[32]. Wearables are becoming more ubiquitous, less obtrusive, have more computing power and are able to operate on battery long enough or use energy harvesting means [33, 34]. This part of research contribution illustrates an emergency notification system based on a wearable including an LPWAN, a foot gesture interface and a NN classifier.

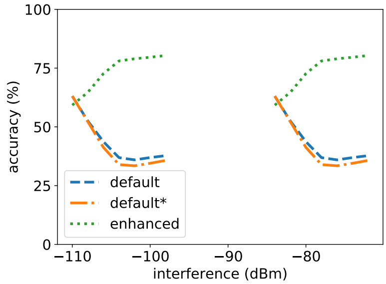
The robust communication offered by an LPWAN can be utilized in an emergency system where the PRR is very crucial. Furthermore, long range communication enables an independent operation in smart cities environment since there is no dependency on a smartphone or a short range gateway



(a) Spreading Factor (SF)



(b) Channel CF offset



(c) Interference degree at the sender

Figure 2.4: The accuracy of the default CCA algorithm and the enhanced version. Each subfigure shows one of the three factors affecting the sender's ability to detect the interfering signal

for communication. However, the main scenario we focus on is when a user is in a case of a possible threat and is willing to send an alert message in discreet, without being noticed by a possible perpetrator. In that case, the user can send an alert message by using the system we propose. Thus, besides the robustness offered in the communication, there is a requirement that the trained gestures should be accurately identified. Distinguishing activities from foot gestures with regular computational methods with the low-cost hardware we use here is challenging. Therefore we developed the NN classifier which is able to accurately identify gestures from physical activities.

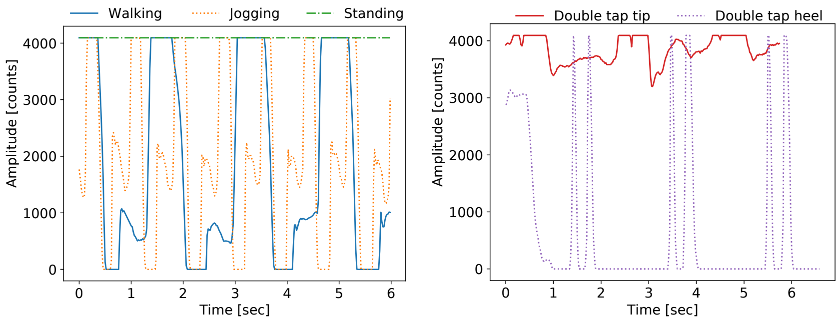
Research Question: The research question we raise in this part of the contribution is the following: Can a low-cost foot-gesture interface be used to identify foot gestures during physical activities (walking, jogging, etc) in a long range emergency system use case, within a smart city environment?

Method: In order to give an answer to the research question, the first step was to build a wearable prototype. The prototype is based on a regular shoe and low cost, off-the-shelf electronics. Figure 2.5 presents the prototype which is comprised from two force sensors deployed above the shoe sole connected to an LPWAN. The objective here is to see how accurately the interface is able to identify gestures in different environments while the user is doing other activities, such as jogging, walking etc. We proposed a lightweight NN classifier, which is implemented into the MCU even though the evaluation was carried out offline, after we have gathered a dataset of two individuals. The rationale behind this method was to perform a systematic analysis on the statistics of the results, but also to be flexible and have the option to optimize and try other models.

(a) (b) (c)

Figure 2.5: The prototype was based on a regular shoe including two force sensors, one at the the tip of the shoe (a), one at the heel (b), which were connected to an LPWAN node (c)

To obtain the dataset, two individuals tried the wearable indoors, using a treadmill and outdoors in a regular urban environment. The scenario was to perform three specific activities, walking, jogging, standing and two foot gestures, a double tap at the tip and a double tap at the heel. Afterwards the dataset was divided 80% for training the classifier and 20% for testing it. A part of the raw measurements are depicted in Figure 2.6, where in 2.6a, the investigated activities are shown and in 2.6b, the gestures we focused on are shown. These two, gestures and activities, are represented with a set of digital values between 0 - 4095 given via the Analog to Digital Converter (ADC). In Figure 2.6a we see that the force sensor saturates some times specifically when the user was standing. This did not affect the accuracy of our results. However we have to mention that if we target more complex activities or gestures the accuracy might drop. This can be solved by replacing this force sensor with another one which is able to tolerate more weight.

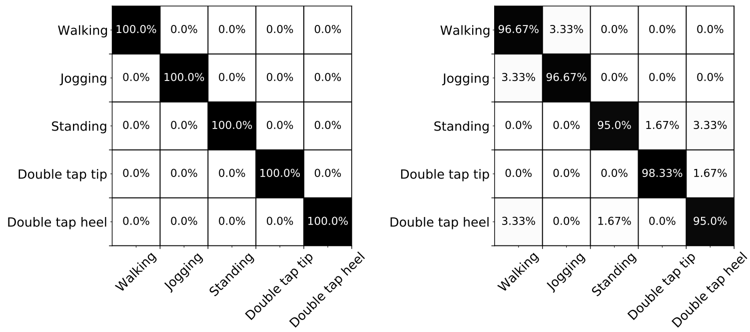


(a) Activities (b) Gestures

Figure 2.6: Raw measurements of the investigated gestures and activities from the back sensor

Evaluation: During the evaluation, the classifier was trained and evaluated per individual because gait pattern is a unique biometric characteristic [35]. In addition, the purpose was not to create a universal classifier, but to propose a lightweight classifier which is delivering the required performance when it is used with a low cost wearable and the focused application scenario instead. Furthermore, it is common for commodity wearables that users are able to register a specific gesture through an offered procedure.

Figure 2.7a represents the accuracy indoors and Figure 2.7b the accuracy outdoors from one of the two individuals who participated in the use case. There is a slight drop when the user is using the wearable outdoors and this can be explained from the fact that the environment outdoors is more unstable and less controlled in comparison with the treadmill we used inside. In general all the gestures/activities were classified with 95% accuracy or more and the average accuracy for both environments is 98.16%. The results illustrate that the interface is accurate for this scenario and it can operate well both indoors but also outdoors, where the environment is an urban street and it is more unstable. The proof of concept indicates that this approach can be used in similar scenarios like activity monitoring applications. Another case that the prototype can by used, is as a platform to collect data and evaluate ML models in contexts like tinyML [36].



(a) Indoors (b) Outdoors

Figure 2.7: Experimental results indoors and outdoors from person A. The Y axis represents the ground truth and the X axis represents the NN-classifier output

2.5 Synchronization over long range for sports applications

Professional sport training has been transformed a lot during the last years. National level teams or topmost clubs make investments on new technologies and facilities designed to monitor and improve the well-being and performance of the athletes. Therefore, there is an emergence on research focusing on sports technology and wearables. In this research we focus on K2 and K4 kayak and we monitor the level of the paddling synchronization between the kayak athletes. The optimal level of paddling synchronization between the athletes is still an open question [37]. There have been attempts to implement commercial products to monitor the performance in kayak training such as Oar Power Meter [38], which is a device that can be attached on the shaft and it includes several sensors to capture metrics like Stroke Rate (SR), force, pace and others. This device is transmits wirelessly all this data to a smartphone or a tablet in the kayak. The problem with this approach is that the athletes might need to control this device and this interaction can be disrupting towards the performance of the athletes.

To tackle these issues it is required a system which is able to offer long range communication for control and time synchronization like LoRa but the drawback with this radio is that it's duty cycle is restricted from rigid regulations. For instance in E.U. the duty cycle for LoRaWAN is set to 1%, which means that if the payload in a transmitted packet is 65 bytes we may have to wait from 13 to 328 seconds (depending the bitrate) before being allowed to send the next packet. To this end, we propose a dual radio system, including a LoRa and BLE radio, designed to monitor kayak training athletes. The LoRa radio is used for offering time synchronization by utilizing the time reference obtained by a LoRa gateway. Furthermore, the proposed system is able to provide remote access to the data and remote control to be able to change the feedback to the athletes during the training session. Offering long range synchronization is enabling also the option to associate the sensor readings with computer vision systems [39] which are used to monitor performance in sports. The BLE radio is used to avoid the rigid duty cycle regulations and be able to handle larger traffic in shorter range, for instance within the kayak.

Research Question: The research question that is investigated in this part is the following: Can we have long range time synchronization but still not be restricted by duty cycle limitations locally?

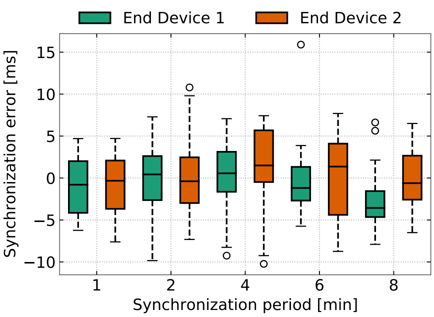
Method: The method we selected to answer the raised research question in this part involved a set of experiments with real hardware to evaluate the time synchronization of the system but also a simulation where real hardware was involved to evaluate how the system performs in the context of kayak training.

We refer to the dual radio nodes as End Devices (EDs) for practical reasons. In the first part we used two EDs, a LoRa gateway and a logic analyzer. The idea here was to follow the synchronization scheme we propose and since all the involved hardware were directly connected to a logic analyzer, we were able to check the synchronization error between the EDs and the gateway. This method would not be possible if we wanted to achieve a synchronization level of microsecond scale, since there several delays which cannot be captured with this method, like the propagation delay generated by long range communication. We performed a set of experiments and we used different synchronization periods to simulate LoRaWAN protocols which have limited duty cycles. Furthermore we checked how the EDs clock drift is able to contribute to the synchronization error or not.

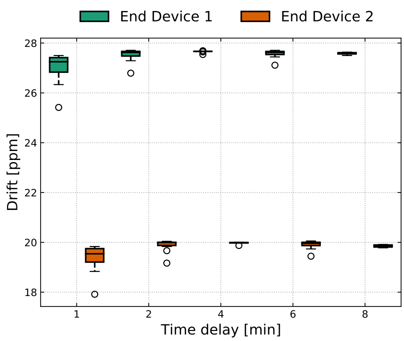
Next we attempted to simulate the training process and we used three EDs and the LoRa gateway. In real K2 or K4 kayaking the athletes try to synchronize in catching the same water phase. The athlete sitting in the front does the first stroke and the the rest athletes should follow with a small offset to catch the same water phase. This water phase can be as short as 250 ms in competition speeds. In the simulation part one of the three EDs is supposed to be one of the kayak athletes who is at the front position and the rest athletes should try to follow her/his paddling. Hence, one of the EDs was sharing a timestamp, which was generated periodically, with the other

EDs. The frequency of generating these timestamps represents the stroking rate in kayak paddling to check if the timestamps are delivered on time to the other athletes, to be able to adjust their own paddling pace based on the feedback. Furthermore in a later experiment we check what is the synchronization error of the timestamps which are generated in those scenarios.

Evaluation: We define the synchronization error of the EDs as the the time offset between an ED and the LoRa GW after the synchronization scheme has been executed. This is the metric we use to evaluate the synchronization scheme. The synchronization error of the EDs should not be confused with the paddling synchronization of the athletes which is the time offset between the stroke of the first athlete in the kayak to the rest of the athletes. As it is explained at the method part two EDs are involved here and Figure 2.8a and Table 2.1 shows their results. The purpose of this experimental session was to evaluate the synchronization scheme but also to identify a synchronization period which is performing well in the application scenario we focus. The average synchronization error for most of the cases is 1 ms or lower except the case where the synchronization period is 8 minutes. It seems that there is no significant relation between synchronization period and the synchronization error up until the former becomes higher than 6 minutes. This behaviour can be explained from the fact that the time reference obtained from the LoRa gateway is down to millisecond scale. We see that the minimum average synchronization error was achieved when the synchronization period value was 2 minutes.



(a) Synchronization error



(b) Drift rate

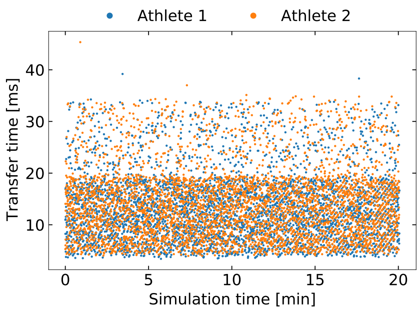
Figure 2.8: Synchronization error and drift rate for different time intervals

In order to present that the paddling synchronization feedback is able to be transmitted on time, among the athletes during the training session, we

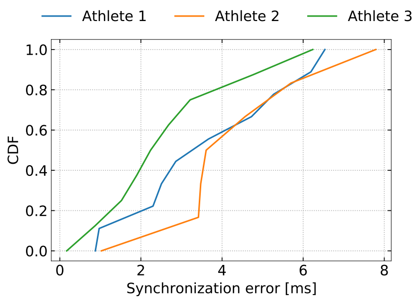
Time	Synchronization Error (ms)		Drift rate (ppm)	
	Device 1	Device 2	Device 1	Device 2
1 min	-1.04 ± 3.2	-0.73 ± 3.2	$25.002269 \pm 6.3 \cdot 10^{-9}$	$25.002193 \pm 5.9 \cdot 10^{-9}$
2 min	-0.23 ± 4.03	0.13 ± 3.8	$25.002275 \pm 2.6 \cdot 10^{-9}$	$25.002198 \pm 2.5 \cdot 10^{-9}$
4 min	0.47 ± 3.2	1.69 ± 4.4	$25.002276 \pm 4.2 \cdot 10^{-9}$	$25.002199 \pm 3.6 \cdot 10^{-9}$
6 min	-0.34 ± 4.34	0.24 ± 4.8	$25.002275 \pm 1.7 \cdot 10^{-9}$	$25.002198 \pm 1.8 \cdot 10^{-9}$
8 min	-2.45 ± 3.9	0.05 ± 3.8	$25.002275 \pm 4.6 \cdot 10^{-9}$	$25.002198 \pm 4.7 \cdot 10^{-9}$

Table 2.1: Results illustrating the accuracy error and the drift rate (mean and standard deviation) throughout different scenarios

run a simulation where generated events representing paddling synchronization feedback are transmitted, following a period which stands for the stroke rate. Figure 2.9a shows that the transfer time of the generated events when the stroke rate is 200. We see that the transfer time is 45 ms or less for all the cases which is adequate since in this stroke rate every stroke will last no more than 300 ms. In that sense the kayak athletes will be able to receive the feedback on time and adjust their paddling if they have too. Figure 2.9b illustrates that the synchronization error of the timestamps generated with a similar frequency as the stroke rate in different experiment and we see the error is 8 ms or less which is within the time synchronization error we target.



(a)



(b)

Figure 2.9: Transfer time of synchronization feedback for stroke rate 200 strokes/min among athletes in (a) and the synchronization error of the obtained timestamps during the simulation in (b)

In overall we see that the proposed system is able to fulfil the requirements which was designed for. Thus, it is enabling a new way to monitor and control kayak training and capture the performance remotely by taking advantage of the synchronization scheme and the dual radio platform.

To the best of our knowledge, this is the first approach in the scientific literature which is leveraging a LoRa radio to offer long range control and synchronization and a BLE radio used for higher traffic communication in short range.

Chapter 3

Related Work

This chapter presents a summary of related work which is balancing between the contributions presented in this thesis and the scientific literature describing the topics this thesis is related to. The structure of this chapter is organized as follows: Section 3.1 relates to contributions from Paper A and B, Section 3.2 relates to contributions from Paper C and Section 3.3 relates to contributions from Paper D.

3.1 Co-existence issues among LPWAN platforms

Quantifying and mitigating CTI is a topic that has been investigated thoroughly in the sensor networks community [16, 17, 18]. Many researchers proposed different kinds of solutions to avoid CTI in these particular networks such as duty cycling, Time Division Multiple Access (TDMA) protocols, CTI source identification to optimize the Medium Access Control (MAC) protocol accordingly and many others. LPWANs are different in many terms (topology, physical characteristics, communication range), therefore we decided to investigate the CTI between two emerging LPWANs to provide an insight on this problem. The next paragraph mentions a number of research efforts that target quantification and mitigation interference in LPWANs.

In [40] the authors report how much LoRa can tolerate CTI from technologies that operate on the same frequency band as Sigfox, Z-Wave, and IO Home Control. The results show that it is crucial if a LoRa transmission is interfered during the preamble phase. In that case, the PRR might drop by 20%. If the CTI occurs during the payload transmission, the PRR drop is insignificant, very close to 0%. Afisiadis et al. in [41] evaluate LoRa performance under white Gaussian noise and interference from another LoRa radio. The authors extend an interference model to investigate chip and phase misalignment between the transmitting and interfering signal to estimate the error rate in terms of Symbol Error Rate (SER) and Frames Error Rate (FER). In [42], the authors research the effect of narrowband and wideband CTI, represented from a model described in [43] on LoRa signal in terms of Bit Error Rate (BER) and Signal to Noise plus Interference (SNIR). As expected LoRa is more tolerant to narrowband interference. The authors of [44] propose a model which accounts for LoRaWAN subject to IEEE 802.15.4g CTI. Afterwards they use a dataset from real experiments to propose two algorithms that optimize LoRaWAN configurations given a reliability threshold. Marquez et al. in [45] carried out an empirical study reporting the level of CTI LoRa might experience in the wild. In addition the authors introduce a model based on the measurements, which intends to increase the robustness of LoRa. Results illustrate that LoRa can experience 0% PRR if the interference within its range is up to 14 dBm. An empirical research of interference between LoRa networks is presented in [46]. The authors investigate the case between two LoRa nodes when one is using Chirp Spread Spectrum (CSS) and the Frequency Shift Keying (FSK) modulation. The results show a variety of heavily and lightly interfered packets which is making it difficult to draw solid conclusions.

All these approaches focus mostly on how LoRa might be affected by CTI, but our work in Paper A reports also on how LoRa can affect the performance of other LPWAN technologies within its communication range. We consider this case more crucial because other LPWANs have been proven less robust than LoRa [47]. Furthermore, our work is based on a systematically highly controlled method that lead to a vast amount of results, quantifying the degree of tolerance in terms of PRR between LoRa and IEEE 802.15.4g and vice versa.

Proposing methods to mitigate interference is a also very popular topic in the same scientific community. A common method to mitigate interference in the cognitive radio, but also to the sensor network communities is to identify the source of interference (i.e. Wi-Fi) to enforce an appropriate strategy. One of the early attempts in [48], is proposing White-Fi, a Wi-Fi like system operating over UHF white spaces which is taking advantage of known preambles to identify other radio systems. Hong et al. introduces DOF [49], which is using a Support Vector Machine (SVM) to classify CTI sources, such as Wi-Fi, Bluetooth, Zigbee, based on their different physical signal properties. Chan et al. in [50], introduce DeepSense which is a carrier sense mechanism designed to identify and avoid transmissions from 26 different LPWAN protocols based on a Neural Network (NN).

The contribution we present in Paper B is able to detect LoRa transmissions based on the Clear Channel Assessment (CCA) mechanism included in the IEEE 802.15.4 [51] standard in combination with a proposed Neural Network classifier. The introduced mechanism is not depending on any hardware accelerator due to its lightweight design and it is fully compatible with the IEEE 802.15.4 standard.

3.2 Foot gesture interfaces in IoT

Foot gesture interfaces emerged since the very beginning of HCI. During the last decade there is an increased utilization of foot gesture interactions which is enabled due to the decreasing cost of low power electronics and the development in sensing technologies. For instance in [52], an augmented reality game based on a smartphone is developed. The purpose of the game is to control a virtual ball with hand or foot gestures using the smartphone display. The authors conclude that a multimodal interaction is making the game more interesting based on the results. According to [53], hand and foot gestures can be combined to increase the speed of multitasking on tabletop systems. Felberbaum et al. in [54], analyze and extract foot gestures during different user conditions, namely: standing in front of a display, sitting down in front of a desktop display, and standing on a projected surface. In addition, a metric to quantify a gesture's preference to a task is introduced. Footscketch, a foot gesture recognition app is developed in [55], utilizing accelerometer data and a Dynamic Tree Warping algorithm. The scope is to associate tasks with foot gestures. The results show that the time to perform a task can be decreased up to 70% by using Footscketch instead of a touch gesture interface on a smartphone. A similar approach is described in [56], the authors design a foot gesture recognition system based on two electromyography (EMG) sensors. The sensors are attached at the lower knee, and in combination with a Support Vector Machine (SVM), the system is able to recognize a set of trained foot gestures which are supposed to aid musical instrument tasks.

The approach presented in Paper C is demonstrated with an application scenario where a user is under a possible threat and wants to send a notification message in discreet. Nevertheless, the system we propose can be used in other application scenarios as well, such as sports, healthcare, retail, and any case where a user cannot use her hands because they are occupied, but wants to perform a task which can be actuated wirelessly. Some other advantages of our work is that it can be used as a stand alone system (due to the long range communication, no smartphone/router is required), it is unobtrusive, its low-cost build on off-the-self components and is compatible with other mainstream wireless technologies beside LPWAN.

3.3 Synchronization in low power wireless communication

Time synchronization in sensor networks is a topic which has been examined in depth. Time synchronization is being offered frequently through a message exchange scheme and a number of time points which are registered to account for clock drift and synchronization rate with a central time reference. One of the first research attempts in low power wireless synchronization is described in [57], where a Reference Broadcast Synchronization (RBS) scheme utilizes the arrival time of a broadcast message as a reference. In the same manner, the LoRaWAN standard [58] is proposing a scheme for Class B devices where the gateways are transmitting messages to synchronize end devices with accuracy approximately close to 1 sec. A different way to enable synchronization in low power wireless networks is using the Time Slotted Channel Hopping (TSCH) mechanism [59]. In TSCH, the end devices are hopping through a number of channels to ensure reliability. This is achieved by a fixed schedule enforced by a central entity which is orchestrating and managing the schedule. In [60], a synchronization at the scale of hundreds of μsec is demonstrated in a sensor network by using TSCH. A Flooding architecture is a way that can ensure high accuracy in a sensor network and it has been used several times. In [61], Ferrari et al. introduce Glossy, which is taking advantage of constructive interference of IEEE 802.15.4 symbols to use in a flooding architecture which is offering high reliability and a synchronization accuracy bellow 0.5 μsecs. A synchronization scheme that is designed for LPWANs and based on a message exchange scheme is presented in [62]. The authors demonstrate that a synchronization of 2 μsecs can be achieved by measuring low level deterministic delays and include them in the proposed synchronization scheme.

All the research attempts mentioned in the previous paragraph either have high traffic requirements due to the flooding architecture or the synchronization degree that they offer is not fitting our application scenario which is a synchronization degree close to 1 msec. The approach mentioned in [62] meets this requirement, but the bitrate and channel utilization regulations do not meet the other requirement of the application we focus in this thesis, which is to be able to share the paddling synchronization level between kayak athletes during training. The traffic demands cannot be met with an LPWAN and the long range synchronization cannot be met with a traditional sensor network. To this end in Paper D, we describe how we designed a dual radio platform which uses LPWAN for long range synchronization and Bluetooth Low Energy (BLE) for local communication in a kayak.

Chapter 4

Summary of appended papers

4.1 Paper A

Charalampos Orfanidis, Laura Marie Feeney, Martin Jacobsson, Per Gunningberg. **Investigating interference between LoRa and IEEE 802.15.4g networks.** *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*

Summary: Paper A presents a systematic investigation between the CTI interactions of two popular LPWAN and Wireless Smart Utility Network (Wi-SUN) platforms: LoRa [12] and IEEE 802.15.4g Wi-SUN [63]. Both investigated radios are using the ISM band which is a popular option in IoT due to no spectrum license cost and administration overhead. Offering the option to deploy a wireless network in that simple manner and free of cost is increasing the amount of independent networks that might operate within the same environment and thus generating CTI which might affect the robust performance of a network.

Highly controlled experimental scenarios enabled us to quantify the tolerance of one platform to each other and vice versa in terms of packet Reception Rate (PRR). In our setup, the results show, LoRa at moderate bitrate was tolerant enough to Wi-SUN SNIR and its PRR is not affected even when SNIR was 16 dB. For higher bitrate LoRa is also able to achieve decent PRR even when the SNIR is 6 dB. Wi-SUN prove to be more prone to LoRa SNIR which is ascribed to the physical characteristics of LoRa signal are crucial to affect the degree of tolerance on SNIR.

Contribution: I am the main author of this paper. Ambuj Varshney who was a fellow PhD student at Uppsala University at the time, inspired me with the initial idea which I and Laura Marie Feeney developed further and executed a large experimental measurement session to get the results. Laura Marie Feeney's contribution is significant as she contributed a lot to the writing of the draft manuscript as well. The rest of the co-authors contributed with comments on feedback given during the research and the writing part.

4.2 Paper B

Charalampos Orfanidis, Laura Marie Feeney, Martin Jacobsson, Per Gunningberg. **Cross-Technology Clear Channel Assessment for Low-Power Wide Area Networks** *2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*

Summary: Paper B builds on the findings of Paper A. More specifically, after we examined the CTI tolerance between the two wireless platforms, LoRa and IEEE 802.15.4g Wi-SUN, and found that the later is more sensitive to CTI, we decided to examine its mitigation strategies. Therefore Paper B illustrates the impact of LoRa interference on IEEE 802.15.4g (Wi-SUN) networks and the evaluation of the Clear Channel Assessment (CCA) mechanism included in the IEEE 802.15.4g standard. After observing that CCA is not capable of detecting CTI generated by LoRa, we propose an enhanced version which is utilizing a Multi-Layer Perceptron (MLP) classifier. The MLP classifier is trained from a dataset that we obtained by including more than 640,000 LoRa – IEEE 802.15.4 interactions, collected in an automated testbed under highly controlled interference conditions. The results point out that the enhanced CCA version is 30 % more accurate than the default CCA and still compatible with the IEEE 802.15.4 standard.

Contribution: I am the main author of this paper. I identified this problem myself when I realized that CCA is not working as expected under LoRa CTI. Laura Marie Feeney helped me with experiments and contributed to the writing of the draft manuscript as well after receiving feedback from the co-authors. Martin Jacobsson helped me to select the right method to evaluate the proposed mechanism.

4.3 Paper C

Charalampos Orfanidis, Rayén Bel Haj Hassen, Armando Kwiek, Martin Jacobsson. **Intelligent Foot Gesture Interface for Resource-**

Constrained IoT Devices. *Submitted to international conference*

Summary: Paper C explores the potential of how LPWAN can be combined with a foot gesture interface to implement an emergency notification system based on a wearable system. Hence, we introduce a prototype which is based on a regular shoe and the main parts are an LPWAN and a foot gesture interface on the top of shoe sole. The interface is built with force sensors connected to the Microcontroller Unit (MCU) that controlls the LPWAN. The scope here is that the user can send a notification in discreet during a possible threat. In addition, we designed a Neural Network (NN) classifier which is trained to distinguish activities like walking and jogging from the pre-defined foot gestures. The results illustrate that the prototype along with the classifier is able to distinguish the gestures from the investigated activities with at least 96% accuracy evaluated on two different users.

Contribution: I am the main author of this paper. I got inspired from a side project on smart-shoes and conceived the idea that LPWAN can be combined with a foot gesture interface to implement an emergency notification system. Rayén Bel Haj Hassen and Armando Kwiek contributed a lot to this project by creating the prototype and executing the experiments under my supervision. The project is a part of their BSc thesis. I wrote the draft manuscript after receiving feedback from the co-authors.

4.4 Paper D

Charalampos Orfanidis, Linus Remahl, Xenofon Fafoutis, Jonas Wåhslén, Hans Rosdahl, Johnny Nilsson, Martin Jacobsson. **Synchronization over Long Range: A kayak training scenario.** *Submitted to international journal*

Summary: Paper D researches how LPWANs can be utilized in sports technology and instrumentation. Particularly we examine K2 and K4 kayak where the paddle stroke synchronization among the athletes is crucial for the performance. Consequently, we developed a dual radio platform which is able to monitor and provide the paddling synchronization degree among the athletes in order to improve their technique during the training sessions and investigated it thoroughly afterwards. Moreover, the long range synchronization is able to convey the synchronization degree to third parties, for instance, to pose estimation systems captured by computer vision, and other sensor fusion purposes.

Contribution: I am the main author of the paper. Jonas Wåhslén gave me the initial idea and then I developed it further to the outcome presented in Paper D, after several research discussions and brainstorming sessions with Martin Jacobsson and Xenofon Fafoutis. Linus Remahl helped me built the dual radio platform and gave advice on electronics and Printed Circuit Board (PCB) design. Hans Rosdahl and Johny Nilsson helped me a lot to get a better insight of the problem. I executed all the experiments myself and wrote the draft manuscript after receiving feedback and useful comments from the co-authors.

Chapter 5

Conclusions and Future Work

This section presents the conclusions of the thesis, future plans to complete some of the preliminary research results, but also suggestions for new directions that this work can be extended into.

5.1 Conclusions

The emergence of LPWAN initiated a series of developments into the IoT field which affected both research and industry. The fact that one can link networks divided by distance, bring connectivity to remote areas not covered by cellular networks, and introduce new application scenarios by taking advantage of the low power long range communication, made the scientific community to start researching these networks. Most of the initial research attempts focused on exploring the long range aspect or how these networks scale. This thesis is focusing on how robust these networks can be, motivated by their growing popularity. Furthermore, we attempt to utilize the characteristic of robustness on the application layer by proposing approaches that enable application scenarios in health and sports.

Paper A demonstrates an experimental investigation on how two popular LPWAN and Smart Utility Network technologies, LoRa and IEEE 802.15.4g Wi-SUN, tolerate each other in terms of PRR. The systematic method and controlled environment allowed us to explore thoroughly the interactions between the two networks. LoRa can tolerate 6 dB SNIR at high bitrate with high PRR and 16 dB at lower bitrate with acceptable PRR. IEEE 802.15.4g is tolerant to LoRa SNIR depending on the physical configuration of the LoRa radio. The vast amount of results provide insights on designing collision avoidance mechanisms to offer reliability and robustness to higher layers.

After observing that IEEE 802.15.4g is more resilient to LoRa, we decided to evaluate the CCA mechanism included in the IEEE 802.15.4 standard against LoRa-based CTI. The results showed that the standard CCA is not able to identify LoRa CTI reliably because of the heterogeneous characteristics of the two networks. Hence, we introduced an enhanced CCA version, based on a lightweight NN. An experimental evaluation suggests that the enhanced version can increase the overall accuracy of the CCA decision by 30 percentage points.

Paper C presents an approach on how an LPWAN can be combined with a foot-gesture interface in an emergency notification system. To this end, we implemented a NN classifier to distinguish between activities and foot gestures. A preliminary evaluation with two individuals revealed that the classifier is able to distinguish with average accuracy 98.1 % between foot gestures and activities in experiments performed indoors and outdoors. The results demonstrate that a low-cost foot gesture interface can be be a basis for a reliable and robust emergency notification system.

In Paper D we took advantage of the long range and robust communication offered by LoRa combined with BLE to avoid duty cycle limitations locally and we develop a dual radio system which can be used in kayak training. The system follows a simple synchronization scheme that is able to synchronize end devices with a LoRa gateway achieving a synchronization error as low as 2.5 ms. We also carried out a simulation to illustrate that the proposed system is able to deliver sensed data on time within the kayak by utilizing the BLE radio, which is adequate for kayak training.

5.2 Future work

LPWAN and IoT have evolved very rapidly. This part presents some directions that the research of this thesis can be extended to.

One of the motivations for investigating the co-existence of LPWAN is the heterogeneity degree among different LPWAN platforms. These platforms differ in many levels (modulation, protocols, bitrate, etc) and therefore they are unable to communicate with one another. One interesting approach is to develop cross-technology communication protocols which will be to facilitate coordination among diverse LPWAN platforms.

There are a lot of research efforts that focus on Energy Harvesting (EH) in IoT taking advantage of solar, thermal, kinetic and other forms of energy available from the environment to extend the lifetime of a network or to use it as the sole source of energy in battery-free devices. There are very few cases investigating how LPWAN can be powered with energy harvesting means. In addition, it is also very interesting to explore how Intermittent Computing [64], a popular technique to utilize harvested energy and the system operates only if there is available energy, applies on LPWAN networks.

Another interesting direction which might be beneficial for the HCI community is to explore how LPWAN technologies can be used in HCI applications focusing in sports and health. Wireless technologies such as IEEE 802.15.4, BLE and Wi-Fi have been used broadly in HCI but the difference with LPWAN and the long range feature, there is not any requirement for a smartphone/tablet as long as the device operate in a smart city environment. The vision of smart cities describes a scenario where LPWAN gateways will be offering connectivity around the city. Thus, new application scenarios will arrive and, with them, new interfaces which should be researched properly.

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