Model-based Cognitive Communications for Low-power Wireless Networks

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Declaration

This thesis is entirely the candidate's own work except where otherwise accredited and has not been submitted for an award at any other institution.

The research presented in this thesis was carried out in compliance with the MTU Code of Good Practice in Research.

Candidate:	____________________	Date:	____________
Principal Supervisor:	____________________	Date:	____________
Second Supervisor:	____________________	Date:	____________

To my family

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Abstract

Abstract...

Keywords
Low-power Wireless Networks, Receiver-aware Communication, Proactive Medium Access, Models, Interference-aware Communication, Measurements, Prediction

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List of Abbreviations

ACK	Acknowledgement
AP	Access Point
AUC	Area Under Curve
BLE	Bluetooth Low Energy
CCA	Clear Channel Assessment
CCC	Common Control Channel
CDF	Cumulative Distribution Function
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
CTI	Cross-Technology Interference
CTP	Collection Tree Protocol
CTS	Clear To Send
EM	Expectation Maximization
EMA	Exponential Moving Average
FN	False Negative
FP	False Positive
FPR	False Positive Rate

GMM Gaussian Mixture Model

HMM Hidden Markov Model

IAT Inter-Arrival Time

IEEE Institute of Electrical and Electronics Engineers

ISM Industrial, Scientific and Medical

IoT Internet of Things

LPL Low-Power Listening

LPP Low-Power Probing

MAC Medium Access Control

MACA-BI MACA By Invitation

MFR MAC footer

MHR MAC header

ML Maximum Likelihood

MMPP Markov-Modulated Poisson Process

MMPP(2) second-order MMPP

NCLR Normalised Cross-Likelihood Ratio

PDF Probability Density Function

PDR Packet Delivery Ratio

PLR Packet Loss Ratio

PDU Protocol Data Unit

PTS Prepare To Send

RDC Radio Duty-Cycling

RI-MAC Receiver-Initiated MAC

RF Radio Frequency

RFID	Radio-Frequency IDentification
RMSE	Root Mean Square Error
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTS	Ready To Send
SFD	Start Frame Delimiter
SINR	Signal to Interference Noise Ratio
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface
TBNS	Time Between Noise Signals
TDMA	Time-Division Multiple Access
TN	True Negative
TP	True Positive
TPR	True Positive Rate
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor Network

Chapter 1

Introduction

In the last decade, the advancement of wireless Internet of Things (IoT) devices has caused the radio spectrum, especially the unlicensed 2.4 GHz ISM band, to be heavily crowded with smart wireless devices that are used in a wide range of application domains, such as smart cities and environments, smart grids, industrial automation, traffic management and logistics, healthcare and assisted living, agriculture and breeding, public safety and remote monitoring [7, 8, 15, 6]. Irrespective of their specific wireless communication technology, these IoT devices, e.g., sensors, actuators, Radio-frequency Identification (RFID) tags, and mobile phones, are part of the lives of millions of people every day. The rapid growth in the computing ability and the continuous decrease in the cost of electronic devices have paved the way for a new era where such devices can monitor and control everything that we use every day via the Internet.

Soon more and more such smart and interconnected devices will join the already crowded radio spectrum, which brings new challenges, in particular for low-power resource-constrained wireless devices to access the radio medium, to efficiently utilise the scarce frequency spectrum to fulfil the stringent requirements of the ever-growing applications in the IoT domain.

1.1 Terminology

Before proceeding with the contents, it is important to clear the reader's mind with the terminology used in this thesis for dependability, radio frequency interference, noise, sensor node's perspective, white-space, and Wi-Fi.

It is worth noting that according to the literature, dependability of systems comprises of multiple attributes, such as availability, reliability, safety, confidentiality, integrity, and maintainability, and is defined as follows: “dependability of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable to the user(s)” [3, 2]. A wireless network has long availability when the nodes in the network consume low energy. Moreover, having high communication reliability demonstrates a wireless network’s ability to continuously provide correct/required service. Therefore, following the aforementioned definition of dependability, the high energy efficiency and high communication reliability contribute to increasing the dependability of the wireless network.

According to clause F11c of ITU-R V.573-5 [1], radio frequency interference is defined as “degradation of the reception of a wanted signal caused by a radio-frequency disturbance”. In line with this definition, one can only measure the effect of interference on a received signal.

The term “noise” is used in this thesis when referring to unwanted signals (or disturbances) on the IEEE 802.15.4 channels.

In the scope of this thesis, the term “sensor node’s perspectives” is used to describe how a sensor node perceives radio frequency noise.

This thesis uses the term *white-space* to mean *temporal white-space* which is a temporary vacant channel space in time.

IEEE 802.11 is a wireless Ethernet standard that provides interoperability guidelines for vendors that produce wireless devices. Wi-Fi is a wireless technology that is based on the IEEE 802.11 standard. However, commonly IEEE 802.11 and Wi-Fi are used interchangeably, and this thesis follows the same.

1.2 Motivation

One of the major aims of the IoT paradigm is to access data about targeted objects and environments without human interaction as human-entered data has been seen as inaccurate and less cost-effective [13] especially in hard-to-reach places. Therefore, IoT devices, such as low-power wireless devices, are tasked with accurately acquiring required data for applications while maintaining the lifespan of the devices as high as possible to keep the human interaction at its minimum. To this end, high communication reliability and energy efficiency of devices are key requirements of IoT applications, leading to high dependability networks.

A low-power wireless network, such as one based on IEEE 802.15.4 networks, is a collection of wirelessly-interconnected, resource-constrained, distributed data sources that provide information about the environment in which they have been deployed. Upholding the communication reliability and energy efficiency of such a resource-constrained network is essential to fulfil its application requirements.

The original motivating use case of the work presented in this thesis is a design of a reliable in-building fire detection system. The fire detectors/sensor nodes in the fire detection system should periodically check for fire, e.g., by sampling the temperature of the building wherein they are deployed. Periodically generated data is conveyed to a network coordinator that interacts with a server. If a fire is detected, the sampling frequency of the detectors increase, which essentially generates a high amount of data. It is important to note that the radio environment in which the fire detectors communicate is high in noise which is mainly due to fire and other in-building communication systems that share the same frequency band with the fire detectors.

As it is well-known, when located in each other's proximity, wireless communication devices can interfere with each other due to the broadcast nature of wireless transmissions. This phenomenon is called Cross-Technology Interference (CTI) which happens due to the inability of heterogeneous wireless communication devices to coordinate their transmissions in time and frequency. CTI is a major problem, especially in the 2.4 GHz unlicensed radio spectrum, as the said radio band is shared by many heterogeneous devices. Some of those devices operating in the 2.4 GHz unlicensed radio spectrum have high power transmitters, such as IEEE 802.11/Wi-Fi and IEEE 802.15.1/Bluetooth, and high power noise emissions, such as microwave ovens. All these high power uncoordinated emissions, in particular, affects the low-power devices [21, 10], such as low-power IEEE 802.15.4 networks, resulting in increased channel contentions and increased packet losses, which degrade their performance in terms of communication reliability and energy efficiency. Ultimately, CTI under-utilises the precious frequency spectrum as it consumes resources without being used for effective communications.

The research community has primarily approached mitigating CTI in IEEE 802.15.4 networks by focusing on the emission sources. Thus, this thesis has initially focused on IEEE 802.11 noise in the low-power wireless networks as Wi-Fi noise dominates the ISM bands with high transmission power (20 dBm). Nonetheless, transmissions of a sensor node could experience interference from multiple emission sources at any given time instance. Thus, focusing on only one source of noise could lead to under-performed networks. There are only a handful of works investigating this with the sensor node's perspective [5, 12, 17], but they look only at one source of noise (i.e., Wi-Fi or IEEE 802.15.1/Bluetooth or microwave ovens) affecting the sensor node. The subsequent study of the thesis has moved toward the sensor node's perspectives to characterise noise from unknown sources rather than individual ones.

1.3 Thesis Goals

The objectives of the research presented here are to improve the performance of IEEE 802.15.4 networks in terms of reliability and energy efficiency and the efficiency of the spectrum usage while adapting to varying noise conditions.

High communication reliability and high energy efficiency make IEEE 802.15.4 networks suitable for the next generation of applications, especially in the IoT domain. In this thesis, a high dependability network is achieved through the design of a novel, decentralised, implicit noise-aware and receiver-aware, proactive medium access control mechanism, which analyses the noise in the environment in advance and estimates noise patterns to predict transmission opportunities for low-power wireless sensor nodes.

The predicted transmission opportunities, i.e., temporary vacant channel spaces in time also known as *temporal white-spaces*, are then utilised by the sensor nodes. Since the proposed technique schedules packet transmissions when noise is not predicted, it decreases packet corruptions, maximising the channel efficiency in the precious unlicensed frequency band.

The radio environment, in particular, the unlicensed band, is a highly dynamic setting as it is crowded by a massive number of devices using different technologies to access the wireless medium [4, 9, 11, 14, 5, 17]. If the transmission schedules of the sensor nodes do not adapt to noise in the radio environment, packet receptions will be interfered with, leading to packet corruptions and data losses. Therefore, adapting the communication algorithm and its parameters in line with dynamic noise is essential to improve the performance of low-power wireless networks.

1.4 Contributions

This section presents the key contributions of this thesis.

1. **A mechanism to analyse patterns in noise traces.** Devices operating in the 2.4 GHz ISM band can interfere with IEEE 802.15.4 networks. This could be from Wi-Fi, IEEE 802.15.1/Bluetooth, or any other device operating in

the aforementioned band generating noise. Thus, a sensor node deployed in the same band perceives noise differently depending on the source of noise as discussed in [11, 9, 22]. Therefore, by considering the source of noise individually, efficient interference mitigation techniques can be developed, e.g., [5, 17]. Even though these solutions perform well in the presence of noise that they are tailored for, there is no countermeasure for the other sources of noise. A robust interference mitigation technique should tackle noise from all possible sources. There is only a handful of research done to mitigate the effects of noise from unknown sources in IEEE 802.15.4 networks, such as work done in [12].

Understanding noise patterns in the deployed environment is essential to mitigate the effects of noise from unknown sources. Therefore, to identify noise patterns, the radio environment is sampled for collecting noise measurement traces. These traces are characterised by the mean Time Between Noise Signals (TBNS) and the number of identified noise signals within a selected time period. The two-dimensional distribution of the aforementioned two metrics and a tool called “Normalised Cross-Likelihood Ratio (NCLR)” are the key to identify noise patterns.

2. **A mechanism to use noise patterns to predict noise-free opportunities for transmission.** One of the goals of this thesis is to predict transmission opportunities for low-power wireless devices. In this thesis, a noise model is used to estimate noise patterns and a white-space model is used to predict noise-free opportunities for nodes. These models are parametrised based on the noise conditions in the deployed environment. The parametrisation of the models is done with the help of knowledge about the noise patterns. The models are trained to have different parameter sets that are suitable for varying noise conditions and the most suited parameter set is chosen based on the performance of the wireless network.

3. **A protocol that utilises the prediction mechanism to identify rendezvous points for low-interference communication.** The backbone of this thesis is the model-based receiver-aware MAC protocol (LUCID). The receiver-initiated communication concept for wireless ad hoc networks came with the work presented in MACA By Invitation (MACA-BI) [20] in 1997, wherein the receiver polls one of its neighbours asking if it has a data packet to send. In 2008, [19] proposed a receiver-initiated asynchronous duty-cycle

MAC protocol for finding the rendezvous point between the sender and the receiver. However, these methods cannot guarantee collision-free transmissions in the network with hidden terminals. In this work, the collected noise traces are exploited to build noise/white-space models that estimates noise patterns and predicts transmission opportunities, also known as white-spaces, for low-power wireless nodes. The predicted white-spaces from the white-space model is the key to finding the rendezvous points between a transmitter and a receiver. To this end, the receiver's white-space model is used by the transmitter to decide the time slot during which it transmits packets. As the transmitter transmits packets in a round-robin fashion in the dedicated sub-slot within the selected time slot, the technique can minimise the collision of packets with other nodes that transmit in the same time slot. Therefore, LUCID can effectively tackle the hidden terminal problem as well.

LUCID uses a hybrid time slotted radio medium access mechanism for scheduling transmissions. This technique uses good properties of both centralised and decentralised scheduling paradigms, wherein tight time synchronisation is coordinated by a central entity, the network coordinator, while the actual transmission scheduling is done locally in the nodes. As it uses time slots, time synchronisation is a vital part of the proposed interference mitigation solution. This is achieved through updating clock drifts of individual nodes in the low-power wireless network upon receiving periodic time synchronisation packets flooded by the network coordinator. The transmission timing of the individual node is decided by the node itself locally with the use of its receiver's white-space model, which predicts white-spaces at the receiver. The transmission opportunities predicted by the receiver's white-space model are the key to deciding the transmission timing w.r.t. time slots of individual nodes.

In the presence of noise, low-power IEEE 802.15.4 nodes need to adapt to changing noise patterns and adjust their transmission schedules in order to avoid interfering transmissions and maximise the performance of their wireless network. As a model-based solution is proposed to tackle interference, the model parameters need to be tuned in line with the dynamics of noise to minimise transmission corruptions and losses, which eventually improves the energy efficiency of the wireless network. Therefore, to have packet loss awareness and adaptation to packet loss dynamics, continuous monitoring of data communication reliability is done to identify change points. Detection of such change points triggers the re-parametrisation of the white-space model to align with the new noise patterns.

It is noteworthy that LUCID is designed and evaluated for periodic data applications. It is not realisable with currently available off-the-shelf low-power IEEE 802.15.4 nodes due to the CPU and memory requirements of the protocol for *a*) analysing the noise patterns, and *b*) predicting future noise-free windows. Nonetheless, LUCID can be implemented with modern processors, such as ARM Cortex CPUs, which have enough memory and CPU power.

4. **A large set of real-world indoor noise traces.** To properly parametrise the noise model that can estimate noise patterns, it is essential to accurately understand the radio environment. This is the foundation of the solution proposed in this thesis to mitigate the effects of noise in IEEE 802.15.4 networks. To this end, a large set of real-world, indoor noise traces are collected by considering the noise source's as well as the sensor node's perspectives.

    - noise source's perspectives: as the dominant indoor interferer [16], Wi-Fi creates heavy noise on IEEE 802.15.4 channels with much higher transmission powers than low-power sensor nodes. The situation is exacerbated by the overlapping nature of wide Wi-Fi channels, which generates aggregated disturbances on sensor nodes. In this work, the aggregated Wi-Fi disturbance is measured with the help of the noise traces collected by Wi-Fi dongles in two distinct indoor environments, OFFICE, an office building, and HOME, a shared apartment in a student dormitory. These locations of the experiments are chosen to cover different noise conditions. The outcome of the measurements is a set of timestamps at which Wi-Fi packets are detected.
    - sensor node's perspectives: to gain more understanding about the noise patterns as perceived by sensor nodes, the investigations are moved toward sensor node's perspectives in which noise traces from unknown sources are collected by TMote Sky [18] sensor nodes. The acquired datasets consist of noise traces from three measurement campaigns in the same two indoor environments mentioned before. Unlike Wi-Fi measurements, these traces do not differentiate the source of noise and constitute noise from unknown sources as seen by sensor nodes. During

the measurement campaigns, timestamps of the start of noise detected by the sensor nodes are collected. The design of the data traces collection is informed by the interest in understanding the noise and its short- and long-term, channel, and location variations. Although the sensor node platform that is used can be deemed obsolete, the measurements are valid for all contemporary radios as the Clear Channel Assessment (CCA) threshold is set to -77 dBm in the sensor node.

The datasets expose several insights that may be of value to the broader community. The acquired Wi-Fi traces are characterised by Wi-Fi frame Inter-Arrival Time (IAT), while the characterisation of noise traces from unknown sources is done based on two metrics: mean (TBNS) and the noise signal count within a selected time period. The two metrics help to characterise unknown noise in two dimensions, which is more accurate than characterising it with a single metric. The noise characterisation revealed the distinct properties of unknown noise on different IEEE 802.15.4 channels, locations, and environments. Moreover, the collected datasets can be used to reproduce realistic indoor noise patterns in a precise and repeatable way in simulators and/or testbeds. Existing tools like JamLab [5] can use probability distributions extracted from the collected datasets to generate indoor noise patterns. Furthermore, the datasets can also directly inform CTI mitigation strategies.

1.5 Publications

All the contributions of this thesis are published in peer-reviewed publications as enlisted below.

- I. S. A. Dhanapala, R. Marfievici, P. Agrawal, and D. Pesch. Towards Detecting WiFi Aggregated Interference for Wireless Sensors Based on Traffic Modelling. In Proc. of Int. Conf. on Distributed Computing in Sensor Systems (DCOSS), 2016. (poster presentation).

- I. S. A. Dhanapala, R. Marfievici, S. Palipana, P. Agrawal, and D. Pesch. Modeling WiFi Traffic for White Space Prediction in Wireless Sensor Networks. In Proc. of the 42nd Conf. on Local Computer Networks (LCN), 2017. (short paper).

- I. S. A. Dhanapala, R. Marfievici, S. Palipana, P. Agrawal, and D. Pesch. Modeling WiFi Traffic for White Space Prediction in Wireless Sensor Networks, 2017. arXiv:cs.NI/1709.08950. (expanded paper).

- I. S. A. Dhanapala, R. Marfievici, S. Palipana, P. Agrawal, and D. Pesch. White Space Prediction for Low-Power Wireless Networks: A Data-Driven Approach. In 14th Int. Conf. on Distributed Computing in Sensor Systems (DCOSS), 2018. (long paper).

- I. S. A. Dhanapala, R. Marfievici, and D. Pesch. LUCID: Receiver-aware Model-based Data Communication for Low-power Wireless Networks. (journal paper in progress. Submitted to IEEE Access and two out of three reviewers accepted it with minor changes. Draft version available at http://arxiv.org/abs/2107.02271).

- I. S. A. Dhanapala, R. Marfievici, and D. Pesch. Dataset: Model-based Cognitive Communications for Low-power Wireless Networks, 2021. [Online] Available: https://doi.org/10.5281/zenodo.5594639. (data set).

1.6 Thesis Outline

Thesis outline...

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Appendix A

How to install LaTeX

Windows OS

TeXLive package - full version

1. Download the TeXLive ISO (2.2GB) from https://www.tug.org/texlive/
2. Download WinCDEmu (if you don't have a virtual drive) from http://wincdemu.sysprogs.org/download/
3. To install Windows CD Emulator follow the instructions at http://wincdemu.sysprogs.org/tutorials/install/
4. Right click the iso and mount it using the WinCDEmu as shown in http://wincdemu.sysprogs.org/tutorials/mount/
5. Open your virtual drive and run setup.pl

or

Basic MikTeX - TeX distribution

1. Download Basic-MiKTeX(32bit or 64bit) from http://miktex.org/download
2. Run the installer
3. To add a new package go to Start » All Programs » MikTex » Maintenance (Admin) and choose Package Manager

4. Select or search for packages to install

TexStudio - TEX editor

1. Download TexStudio from
   http://texstudio.sourceforge.net/#downloads

2. Run the installer

Mac OS X

MacTeX - TEX distribution

1. Download the file from
   https://www.tug.org/mactex/

2. Extract and double click to run the installer. It does the entire configuration, sit back and relax.

TexStudio - TEX editor

1. Download TexStudio from
   http://texstudio.sourceforge.net/#downloads

2. Extract and Start

Unix/Linux

TeXLive - TEX distribution

Getting the distribution:

1. TexLive can be downloaded from
   http://www.tug.org/texlive/acquire-netinstall.html.

2. TexLive is provided by most operating system you can use (rpm,apt-get or yum) to get TexLive distributions

Installation

1. Mount the ISO file in the mnt directory

   ```
   mount -t iso9660 -o ro,loop,noauto /your/texlive####.iso /mnt
   ```

2. Install wget on your OS (use rpm, apt-get or yum install)

3. Run the installer script install-tl.

   ```
   cd /your/download/directory
   ./install-tl
   ```

4. Enter command 'i' for installation

5. Post-Installation configuration:
   http://www.tug.org/texlive/doc/texlive-en/texlive-en.html#x1-320003.4.1

6. Set the path for the directory of TexLive binaries in your .bashrc file

For 32bit OS

For Bourne-compatible shells such as bash, and using Intel x86 GNU/Linux and a default directory setup as an example, the file to edit might be

```
edit $~/.bashrc file and add following lines
PATH=/usr/local/texlive/2011/bin/i386-linux:$PATH;
export PATH
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;
export MANPATH
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;
export INFOPATH
```

For 64bit OS

```
edit $~/.bashrc file and add following lines
PATH=/usr/local/texlive/2011/bin/x86_64-linux:$PATH;
export PATH
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;
export MANPATH
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;
export INFOPATH
```

Fedora/RedHat/CentOS:

```
sudo yum install texlive
sudo yum install psutils
```

SUSE:

```
sudo zypper install texlive
```

Debian/Ubuntu:

```
sudo apt-get install texlive texlive-latex-extra
sudo apt-get install psutils
```