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Linköpings universitet, Sverige

Titel: Low Latency Wireless Sensor and Actuator Networks: Analysis of LLDN and RT-WiFi
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Publicerad: 2018

Department of Electrical Engineering
Division Integrated Circuits and Systems
Bachelor Thesis
Linköping University, Sweden

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Abstract

In this bachelor thesis, low latency wireless sensor and actuator networks are studied. In particular IEEE 802.15.4e/LLDN and IEEE 802.11g/RT-WiFi protocols. It is investigated if the protocols are suitable for being used in typical industrial automation environments with high update frequencies of around 100 Hz. The protocols are examined on a low level to shed lights on the sources of latency and followed by an analysis of a specific configuration. It is found that LLDN is limited by low transmission rate and RT-WiFi is limited by interference with itself and other appliances. They both work well for update frequencies around 100 Hz.
Thanks to..

I want to thank Magnus Petterson and Adrian Corral at Syntronic, Ted Johansson and Mark Vesterbacka at Linköping University, my new apartment that did not have internet or tv connection for almost a month, myself for writing the thesis.
Abbreviations

CAP - Contention Access Period (Used in IEEE 802.15.4 MAC)
CFP - Contention Free Period (used in IEEE 802.15.4 MAC)
CSMA/CA - Carrier Sense Multiple Access / Collision Avoidance
DIFS - Distributed Inter-frame Spacing (Used by IEEE 802.11)
DSME - Deterministic and Synchronous Multi-channel Extension (MAC sublayer of IEEE 802.15.4e)
DSSS - Direct Sequence Spread Spectrum
FDMA - Frequency Division Multiple Access
GTS - Guaranteed Time Slots
IFS - Inter-frame spacing
ISM - Industrial, Scientific and Medical (frequency band)
LLDN - Low Latency Deterministic Network (MAC sublayer of IEEE 802.15.4e)
MAC - Media Access Control (Part of Data Link Layer)
MFR - MAC Footer
MHR - MAC Header
PHR - Physical Header (Part of PPDU)
MPDU - MAC Protocol Data Unit (MAC Frame)
PHY - Physical Layer
PLCP - Physical Layer Convergence Protocol
PPDU - Physical Protocol Data Unit (Physical Frame)
PSDU - PLCP Service Data Unit (PHY Payload)
SHR - Synchronization Header (Part of PPDU)
SIFS - Short Inter-Frame Spacing
TDMA - Time Division Multiple Access
TSCH - Time Slotted Channel Hopping (MAC sublayer of IEEE 802.15.4e)
WLAN - Wireless Local Area Network

WSAN - Wireless Sensor and Actuator Network

6LoWPAN - IPv6 over Low Power Wireless Personal Area Networks
Nomenclatures

*Gateway* - The central controlling node in a star topology network, which connects the network to another network. In an LR-WPAN network, this would be the PAN coordinator. In a WiFi network, this would be the Access Point.

*Super frame* - A repeating time frame, in which all communication takes place, according to predefined divisions of the frame. The super frame is used in beacon enabled mode of the IEEE 802.15.4 and all time slotted networks.

*Beacon Interval (BI)* - Time between two consecutive beacons.

*Distributed Inter-frame Spacing* - Space in time to wait before transmitting a frame after channel was detected idle. Used in IEEE 802.11 standard.

*Short Inter-frame Spacing* - IEEE 802.11 standard: Space in time between consecutive frames. IEEE 802.15.4 standard: Space between frames.
# Contents

1 Introduction ................................................. 1
   1.1 Project purpose ......................................... 1
   1.2 Problem description and limitations ..................... 1
   1.3 Background ............................................... 2
   1.4 Wireless network technologies .......................... 3
   1.5 Difference between sensors and actuators ............... 4
   1.6 Network setup to be solved ............................. 5

2 Previous Work ............................................... 6

3 Theory ......................................................... 9
   3.1 Network layers ........................................... 9
   3.2 Real time media access control ........................ 9
   3.3 Network topologies ...................................... 10
   3.4 LR-WPAN (IEEE 802.15.4) ................................ 12
      3.4.1 MAC Layer ........................................... 13
      3.4.2 PHY Frame ........................................... 13
      3.4.3 802.15.4e ........................................... 14
   3.5 WiFi (IEEE 802.11) ..................................... 16
      3.5.1 MAC Layer ........................................... 17
      3.5.2 PHY Frame ........................................... 18
      3.5.3 RT-WiFi ............................................. 19
   3.6 Channels in LR-WPAN and WiFi .......................... 21
      3.6.1 Interference between WiFi and LR-WPAN ............ 21

4 Analysis ....................................................... 22
   4.1 Overview ................................................ 22
   4.2 Protocol configurations ................................ 22
      4.2.1 LLDN ............................................... 22
      4.2.2 RT-WiFi ............................................. 23
   4.3 Time slot and super frame duration .................... 24
      4.3.1 LLDN ............................................... 24
      4.3.2 RT-WiFi ............................................. 25
   4.4 Range versus power and rate ............................ 26
   4.5 Multi-star network ...................................... 28
## CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Results</td>
<td>29</td>
</tr>
<tr>
<td>5.1</td>
<td>Time slot and super frame durations</td>
<td>29</td>
</tr>
<tr>
<td>5.1.1</td>
<td>LLDN</td>
<td>29</td>
</tr>
<tr>
<td>5.1.2</td>
<td>RT-WiFi</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Conclusions</td>
<td>32</td>
</tr>
<tr>
<td>7</td>
<td>Discussion</td>
<td>33</td>
</tr>
<tr>
<td>7.1</td>
<td>Power consumption</td>
<td>33</td>
</tr>
<tr>
<td>7.2</td>
<td>Existing implementations</td>
<td>33</td>
</tr>
<tr>
<td>8</td>
<td>References</td>
<td>35</td>
</tr>
<tr>
<td>A</td>
<td>Time plan</td>
<td>38</td>
</tr>
</tbody>
</table>
## List of Figures

1.1 IEEE 802.11, WiFi and RT-WiFi ........................................... 4  
1.2 LR-WPAN (IEEE 802.15.4) based network technologies ................. 4  
1.3 Typical simplified industrial network .................................... 5  
1.4 Illustration of a wireless sensor actuator network ...................... 5  

3.1 Information passing through layers between A and B .................... 9  
3.2 Star network topology ..................................................... 10  
3.3 Multiple star networks ..................................................... 11  
3.4 Tree network topology ..................................................... 11  
3.5 Mesh network topology .................................................... 12  
3.6 IEEE 802.15.4 super frame ............................................... 13  
3.7 IEEE 802.15.4 physical protocol data unit ............................. 14  
3.8 LLDN super frame in discovery, configuration and online states .... 15  
3.9 LLDN MAC frame format, without security ............................. 16  
3.10 LLDN beacon frame, without security ................................ 16  
3.11 LLDN acknowledgement frame, without security ...................... 16  
3.12 IEEE 802.11 MAC frame, general format ............................. 17  
3.13 IEEE 802.11 MAC frame types: management, control and data ...... 18  
3.14 IEEE 802.11 information element ..................................... 18  
3.15 IEEE 802.11 short physical protocol data unit ....................... 19  
3.16 RT-WiFi information element .......................................... 19  
3.17 RT-WiFi super frame format ............................................ 19  
3.18 RT-WiFi time slot format ............................................... 20  
3.19 RT-WiFi data frame format .............................................. 20  
3.20 WiFi and LR-WPAN channels in 2.4 GHz band ........................ 21  

4.1 LLDN super frame used in analysis ..................................... 22  
4.2 LLDN beacon frame used in analysis .................................. 23  
4.3 LLDN data frame used in analysis ...................................... 23  
4.4 LLDN acknowledgement frame used in analysis ....................... 23  
4.5 RT-WiFi time slot used in analysis ................................... 24  
4.6 RT-WiFi super frame used in analysis ................................ 24  
4.7 RT-WiFi beacon frame used in analysis ................................ 24  
4.8 802.15.4 and 802.11g outside range vs power ........................ 27  
4.9 Optimal channel arrangement for nearby WSANs in 2 dimensions .. 28  

5.1 LLDN time slot duration vs payload size ................................ 29  
5.2 LLDN super frame duration vs bit rate ................................ 29  
5.3 LLDN super frame duration vs nodes .................................. 30
LIST OF FIGURES

5.4 RT-WiFi time slot duration vs payload . . . . . . . . . . . . . . . . . . . 30
5.5 RT-WiFi super frame duration vs bitrate . . . . . . . . . . . . . . . . . 31
5.6 RT-WiFi super frame duration vs nodes . . . . . . . . . . . . . . . . . . 31
A.1 Time plan for the thesis work . . . . . . . . . . . . . . . . . . . . . . . . 38
List of Tables

1.1 Description of chapters ............................................. 1
2.1 Process automation areas and their real time requirements. ........ 6
3.1 IEEE 802.15.4 versions time line .................................. 12
3.2 PHY characteristics of frequency bands used in IEEE 802.15.4-2006 and later ............................................................. 12
3.3 Characteristics of IEEE 802.11 a,b,g .................................. 16
4.1 LLDN time slot analysis constants .................................... 25
4.2 LLDN time slot analysis variables .................................... 25
4.3 RT-WiFi time slot analysis constants .................................. 25
4.4 RT-WiFi time slot analysis variables .................................. 26
Chapter 1

Introduction

In this thesis low latency wireless sensor and actuator networks are studied. In particular the LLDN (part of IEEE 802.15.4e) and RT-WiFi (based on IEEE 802.11g) protocols. The purpose is to evaluate their usefulness in industrial settings where update frequencies of up to 100 Hz are required.

The chapters are organized according to table 1.1.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>Problem description and background.</td>
</tr>
<tr>
<td>Previous Work</td>
<td>Looks a bit at earlier work in the field and provides a list of desirable requirements for low latency wireless industrial networks.</td>
</tr>
<tr>
<td>Theory</td>
<td>Focuses on IEEE 802.15.4, LLDN, IEEE 802.11g and RT-WiFi, where details of the protocols are studied in depth, to understand limitations and the origins of the latency.</td>
</tr>
<tr>
<td>Analysis</td>
<td>Analyses LLDN and RT-WiFi using a specific configuration and defines formulas to calculate latencies, or update frequencies.</td>
</tr>
<tr>
<td>Results</td>
<td>Shows results from the formulas defined in analysis chapter.</td>
</tr>
<tr>
<td>Conclusions</td>
<td>Summarizes the important findings.</td>
</tr>
<tr>
<td>Discussion</td>
<td>Touches on things that are not mentioned elsewhere.</td>
</tr>
</tbody>
</table>

Table 1.1: Description of chapters

1.1 Project purpose

Study and analyze low latency protocols suitable for high update frequencies around 100 Hz, for use in industrial environments.

1.2 Problem description and limitations

Research about possible solutions to the application of real time wireless sensor and actuator networks, with very low latency, specifically in industrial settings concerning process automation and control, with the additional delimitations:
• Installations typically are static and changes to the geographical locations of nodes in the network do not occur on a regular basis.

• The number of nodes in each network is less than 50.

• The number of hops is kept to minimum. Single-hop is preferred, but multiple hops might be investigated if enough time.

• Only traffic between the gateway and sensors/actuators are to be be considered. The gateway is assumed to be connected with outside through a fast wired bus with negligible latency.

Then two promising network technologies are chosen to analyze further. Questions to be answered are:

• What wireless network technologies might be suitable candidates considering above delimitations?

• How low latency do the chosen network technologies achieve? And under what circumstances?

• Is it possible to reach 100 Hz update frequency or higher, using at least 10 nodes in the network?

1.3 Background

In industry, a huge amount of sensors and actuators are used. Sensors measure a physical entity and translate this entity into a value that is usually represented by a voltage or a current. The voltage/current is then transferred to the control system by use of electrical wires, often two for each sensor.

Actuators perform a change to a physical entity by using energy to apply a force, which is proportional to a given value. The value is usually represented by a voltage or current, which is transferred from the control system by use of electrical wires.

Sensors and actuators are often spread out over larger distances, which is why a separate pair of wires are needed for each one of them.

Use of electrical wires is a simple and reliable way to communicate values, but comes with a few drawbacks:

• Cost of the wires themselves and cost of the installation of the wires

• Difficult or sometimes impossible to connect moving objects together

• Takes up space, or might be in the way of mobile processes

• Electrically connects different parts of the control system which may worsen the effects of power-surges and over voltage coming from lightning or solar flairs.

• Does not adapt well to changes in location of the connected objects

• Abnormal temperatures may put strain on the insulation of wires

Wireless communication on the other hand, lacks above mentioned drawbacks, but comes with a few drawbacks of its own
CHAPTER 1. INTRODUCTION

• Reliability - Wireless communication is much more complex than a simple wire and have more ways it can fail.

• Interference - Electromagnetic interference from machinery and other networks.

• Life time - The hardware electronics may have limited life time

• Latency - Again the complexity in both hardware and software adds to the overhead of communication.

In the context of real time communication, this latency must be predictable and bounded (have a known maximum value). If the network is also intended to be part of an industrial control loop, the latency should not only be bounded, but also be very low. How low depends on the actual control problem and implementation. To fully support most industrial control systems, an upper update frequency of 100 Hz is desirable, for each individual sensor/actuator.

1.4 Wireless network technologies

Wireless network technologies suitable for wireless sensor and actuator networks are usually based on the LR-WPAN (IEEE 802.15.4) standard, which defines the radio hardware and the Multiple Access Control (MAC) software controlling it. Some technologies like RT-WiFi are based on the IEEE 802.11 standard. Both of these standards are studied in more depth in the Theory chapter.

WirelessHART [3], based on the HART [3] industrial communications standard, adds wireless capabilities while maintaining compatibility with existing HART devices, commands, and tools. It operates in the 2.4GHz ISM frequency band and utilizes IEEE 802.15.4 compatible DSSS radios. It shares the same application level with HART and has its own network- link- and physical layer. It supports TDMA and channel-hopping by own implementation that existed before these features where added to IEEE 802.15.4e. The TDMA slot time is 10 ms. The HART standard has been around for over 25 years. It is a hybrid analog + digital industrial automation protocol. It can communicate over legacy 4-20 mA analog instrumentation current loops, sharing the pair of wires used by the analog host system. It has been an open standard since ’86.

Smart Mesh IP uses IEEE 802.15.4e/TSCH (Time Slotted Channel Hopping) compatible MAC layer. As the name suggests, supports mesh networks.

Following network technologies build on the LR-WPAN standard, with or without modifications and extends the higher OSI-level layers in various ways. They are considered unsuitable for very low latency applications.

• Zigbee extends IEEE 802.15.4 with its own network and application layers.

• Zigbee IP like Zigbee is based on IEEE 802.15.4 standard, but instead of own network layer uses 6LoWPAN which allows devices to be addressed using IPv6.

• Thread builds on IEEE 802.15.4 and 6LoWPAN for IPv6, but defines no application layer.

• MiWi is a proprietary protocol by Microchip based on IEEE 802.15.4 standard. It is meant for simple applications where Zigbee functionality is not needed and only adds its own network layer.
Figure 1.1 visualizes the relations between IEEE 802.11, WiFi and RT-WiFi. In the figure, "+IP" means the addition of parts of the internet protocol and "*MAC" means modification of the MAC layer.

Figure 1.1: IEEE 802.11, WiFi and RT-WiFi

Figure 1.2 visualizes the relations between various LR-WPAN based network technologies. In the figure, green boxes signify protocols that does not deal with anything above MAC level. The other protocols extend beyond MAC level in various ways. 6LowPAN is used as basis for IPv6 extensions, where used. In general, protocols extending beyond MAC level adds to much overhead to be useful in low latency LR-WPAN applications.

Figure 1.2: LR-WPAN (IEEE 802.15.4) based network technologies

1.5 Difference between sensors and actuators

Generally speaking, sensors transmit data into the network, while actuators receive data from the network. However, both sensors and actuators need to both transmit and receive. Sensors need to be told about time slots and/or channel to use, this information can be received either just initially, or periodically. Actuators also can make use of transmission, to acknowledge its reception of data (real time) and provide status information (non real time).

Anything that is transmitting data into the network must do so when no other entity is transmitting, otherwise there is a collision. This is generally solved, in real time settings, by dividing time into slots where each sensor only transmits in its own slot. Another solution is to use different frequency channel for each sensor.
1.6 Network setup to be solved

An industrial process network is often divided into many smaller networks as in figure 1.3. Sensors and actuators are wirelessly connected to a gateway to form a WSAN as in figure 1.4. The gateway connects the WSAN to the Controller low latency network. The controllers are then connected to a TCP/IP network that connects the controllers to the control rooms. The network setup to be studied in this thesis involves only the WSAN part.

![Figure 1.3: Typical simplified industrial network](image1)

![Figure 1.4: Illustration of a wireless sensor actuator network.](image2)
Chapter 2

Previous Work

Industrial WSANs and WSANs in general has seen a lot of research in recent years.

In the paper "INDUSTRIAL WLAN IEEE 802.11 as an industrial communications protocol" Nyman, Sand [1] investigates WLAN performance in industrial environments. However the focus is mainly on throughput and resistance to interference and latency is not part of the measured results.

In the paper "Future Research Challenges in Wireless Sensor and Actuator Networks Targeting Industrial Automation" Åkerberg, Gidlund, Björkman [2] highlights the current needs and future challenges in real time wireless industrial automation. In it is defined some typical requirements of wireless networks for process automation, which in simplified form is given by table 2.1.

<table>
<thead>
<tr>
<th>Area</th>
<th>Delay</th>
<th>Update freq</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring/supervision</td>
<td>ms..s</td>
<td>&lt;1 Hz</td>
<td>Sensors for diagnostics and supervision</td>
</tr>
<tr>
<td>Closed loop control</td>
<td>ms</td>
<td>2..100 Hz</td>
<td>Sensors/actuators connected to PID controllers</td>
</tr>
<tr>
<td>Interlocking and control</td>
<td>ms</td>
<td>4..100 Hz</td>
<td>Process control requiring discrete signaling</td>
</tr>
</tbody>
</table>

Table 2.1: Process automation areas and their real time requirements.

Or generalized further, the latency in the network should be at most a few milliseconds, and the update frequency can be assumed to be as high as 100 Hz. Further points of the paper can be summarized as follows.

- Safety. IWSNs need to have deterministic and synchronized communication in both the up-link and the down-link in order to avoid spurious fail-safe timeouts.

- Security. Most information that is transmitted to and from field devices is usually normalized values of the measured entity and is not sensitive information, unlike the information that resides inside the control system, which is not transmitted on the field networks.

- Availability. Industrial large-scale production availability is of significant importance. Even short and transient communication errors can cause significant production outages. Literature commonly assumes networks with thousands of nodes, while in reality the number of sensors/actuators are usually in the tens, due to availability concerns. Energy saving routing protocol schemes might have severe
and negative impact on the real-time performance. Flooding might be one feasible alternative for usage in mission-critical wireless sensor networks.

• Retransmission. Retransmissions should be kept to a minimum. Information in the network that cannot arrive on time should simply be discarded in favor of newer data. Forward error correction can be used to minimize the need for retransmissions, as long as the additional processing time does not interfere with the latency requirements. In the context of mesh and multi-hop networks, it must be guaranteed that transmissions arrive in the correct order.

• Actuator-support. Currently most standards lack support for actuators. Literature often assumes actuators don’t benefit from being wireless as they already need wires for power. Not all actuators are electric though.

• System integration. The ability to integrate WSAN’s to existing infrastructure is hampered by the lack of open and efficient solutions, which slows down the engineering, commissioning, and maintenance of the system. There are some standardization efforts ongoing though.

• Network size. It is likely that the network will contain up to 50 nodes, rather than 1000’s, if the requirements on high refresh rates are to be met.

• Interference avoidance. Industrial settings may contain many different wireless networks that all operate in the same 2.4 GHz ISM band. Thus, it is very important that a solution can coexist in a radio environment with a large amount of interferences as well as limit its own disturbance.

• Energy consumption. The high refresh rates required makes it hard to operate sensors on low power. Actuators already require their own power supply (unless pneumatic for example). In short, power wires will remain close to sensors and actuators for the foreseeable future. Battery operation, if possible, would pose another problem: scheduled battery maintenance.

In the paper ”Ultra-reliable and real-time communication in local wireless applications” Silvo, Eriksson, Björkbom, Nethi [4] presents a wireless MAC and networking protocol called Real-time Network Protocol (RNP). Designed for small networks with few hops and \( \leq 20 \) nodes. Nodes transmit using TDMA, after a broadcasted initiation by the gateway. Retransmissions use TDMA or CSMA depending on which is faster. Piggybacking of previously received information is used by the nodes to allow multi-hop communication. The protocol is simulated with ns-2 simulator and then implemented on Sensinode Micro.2420 hardware that are equipped with Texas Instruments MSP430 microcontroller and a Chipcon CC2420 IEEE 802.15.4 compliant transceiver. The transmission time for a packet of size 66 bytes is considered to be approximately 2.3 ms under ideal situations using the above hardware. Under test in actual industrial deployment, 5 nodes where used, with transmission slot time of 5ms and transmission frame size of 50ms. With little or no interference, 98% of the transmissions arrived within the first frame and close to 2% in the second frame.

In the paper ”RT-WiFi: Real-Time High-Speed Communication Protocol for Wireless Cyber-Physical Control Applications” Wei, Leng, Han, Mok, Zhang, Tomizuka [6] presents the design and implementation of a real-time high-speed wireless communication
CHAPTER 2. PREVIOUS WORK

protocol, RT-WiFi. It uses TDMA on regular 802.11 WiFi hardware and provides deterministic and real time guarantees on latency. Latencies well below 1 ms are achieved. Compatibility with upper layers like UDP and TCP is part of the design. Only single-hop star network topology is supported currently but multi-hop mesh networks are planned to be supported in future. The original format of the beacon frame is retained by reusing the vendor specific field. Acknowledgments (ACK) of transmissions are part of the specification. In a real life test (with no interference) 99.98% of packets where delivered within assigned 0.5 ms time slot. This looks like a promising technology to fulfill the goal of reliable wireless transmission with delays under 1 ms.

LLDN-MC (LLDN Multi Channel) [10] is based on the IEEE 802.15.4e LLDN MAC behavior mode and aims to increase the possible number of nodes as well as the range of the network by dividing the network into sub-networks forming a two-level tree, where each network communicates internally using its own dedicated channel. The sub-networks require sub-coordinator nodes which are in themselves controlled by the PAN coordinator node. The main idea is that as data frames are collected (assuming a sensor network) from end nodes by the all sub-coordinators simultaneously, the sub-coordinators can aggregate the collected data before passing it on to the the PAN coordinator, thus making savings on the overhead incurred by each MAC frame, as a single frame can now carry data from all the end nodes of a sub-coordinator, to the PAN coordinator. The PAN coordinator and end-nodes need no changes in their protocols, only sub-coordinators need a modified MAC protocol. Simulation results show that with up to 21 end-nodes, standard LLDN is still the better choice, in terms of total cycle time. With 100 end-nodes, an improvement of 44% in cycle time was observed. The downside with LLDN-MC, is the way it eats channels for dinner; with 100 end-nodes the optimal number of sub-coordinators (and therefore channels minus one) is around 10. Also, while the LLDN-MC achieves lower cycle times (higher update frequency), the actual end-to-end latency is still slightly higher than LLDN, because of the extra sub-coordinator hop introduced.
Chapter 3

Theory

IEEE defines standards for wireless network technologies, like WiFi and LR-WPAN mentioned in more detail in sections below. A radio transceiver (transmitter + receiver) constitutes the physical part and is referred to as the "PHY layer" in the standards. Firmware running on an MCU (often integrated with the transceiver hardware), or CPU (on desktop, cell phones, etc) handles Media Access Control and is referred to as the "MAC layer". Wireless PHYs operate in frequency bands, divided into channels. This chapter will focus on the 2.4 GHz Industrial, Scientific and Medical (ISM) band.

3.1 Network layers

Functionality of computer networks follow a layered approach. The Open Systems Interconnection (OSI) model defines seven layers, which in reality often is simplified into five layers [14]: Physical, Link, Network, Transport and Application. The above mentioned MAC layer is a specific part of the Link layer, dealing with Media Access Control.

![Diagram of network layers](image.jpg)

Figure 3.1: Information passing through layers between A and B

Lower layers encapsulate information from higher layers, adding their own layerspecific information, which increases the size of the information that is finally being sent between the physical layers at the bottom.

3.2 Real time media access control

To allow real time communication in the wireless network, either time and/or frequency has to be divided between the nodes, to avoid any kind of collisions, that would otherwise break the deterministic access behavior required.
Time Division Multiple Access (TDMA) is a technique to divide time between nodes transmitting data into the network. It usually requires a network coordinator to broadcast the time slot configuration to the nodes that are to transmit, either initially or periodically, depending on how often changes to the network structure occurs. A big advantage of TDMA is that no destination address need to be transmitted along with the data, as the address is explicit depending only on the actual time slot in with transmission takes place.

Frequency Division Multiple Access (FDMA) allows several nodes to transmit simultaneously into the network, as long as they use different channels. The division takes place in the receiving node(s), where one channel is read at a time. As with TDMA, a network coordinator is usually required to broadcast channel configuration to the nodes to inform them about what channel to use when transmitting. Note that in this scenario channels are assumed to not be overlapping and so are completely independent of each other.

3.3 Network topologies

- Star is the simplest topology. A gateway is connected directly to n end nodes (single hop).

![Star network topology](image)

- Multi-Star contains multiple independent star networks in the same area. To avoid collisions, each network uses its own unique frequency channel(s) or band.
• Tree (star of stars) is a way to extend the range of star type network, where a single gateway (PAN coordinator), communicates with multiple sub-coordinators, coordinating their own sub-network on its own unique channel. The total number of channels used by the tree is one plus the number of sub-networks.

• Mesh is a topology where any node in the network can be a coordinator. Routing algorithms are needed to decide the path of communication through the network. The topology is highly adaptable to changes and non-deterministic behavior in general.
3.4 LR-WPAN (IEEE 802.15.4)

LR-WPAN stands for Low Rate Wireless Personal Area Networks. Intended for embedded, low complexity and low cost applications. The standard defines the PHY and MAC layers and was conceived in 2003 by the IEEE 802.15 working group. The range is around 10 meters indoors. The standard itself does not deal with specific network topologies, rather, it is up to higher level software to handle propagation of messages. Table 3.1 gives an overview of the development of the standard, since the first version in 2003.

<table>
<thead>
<tr>
<th>Year</th>
<th>Version</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>2003</td>
<td>40 kb/s for 868/915 MHz band. 250 kb/s for 2.4 GHz band. 2 PHYs</td>
</tr>
<tr>
<td>2006</td>
<td>2006</td>
<td>Increases rate of 868/915 MHz bands to 250 kb/s. 4 PHYs</td>
</tr>
<tr>
<td>2007</td>
<td>a</td>
<td>Adds UWB and CSS PHYs to a total of 6 PHYs.</td>
</tr>
<tr>
<td>2009</td>
<td>c, d</td>
<td>Additional PHYs for 780 and 950 MHz bands. 8 PHYs</td>
</tr>
<tr>
<td>2012</td>
<td>e</td>
<td>MAC additions: channel hopping, frequency hopping, slotted access</td>
</tr>
</tbody>
</table>

Table 3.1: IEEE 802.15.4 versions time line

Table 3.2 show the frequency bands used in different regions of the world.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Channels</th>
<th>Max rate</th>
<th>Range in/out @ 250 kb/s, 1 mW</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>868 MHz</td>
<td>1</td>
<td>250 kb/s</td>
<td>10/75m</td>
<td>Europe</td>
</tr>
<tr>
<td>915 MHz</td>
<td>10</td>
<td>250 kb/s</td>
<td>10/75m</td>
<td>USA</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>16</td>
<td>250 kb/s</td>
<td>10/75m</td>
<td>Worldwide</td>
</tr>
</tbody>
</table>

Table 3.2: PHY characteristics of frequency bands used in IEEE 802.15.4-2006 and later

Ranges are typical values and depends heavily on transmitting power and types of antennas used, as well as the surroundings (obstructions for example).

The advantage of using sub gigahertz frequencies possible with the 802.15.4, to avoid interference from various appliances in the 2.4 GHz band, is diminished in Europe by the fact that the European 868 MHz band only has room for a single channel. One channel might enough for a single small and isolated network, but this makes it unsuitable for industrial low latency communication, where many nodes are separated into many separate networks, which may overlap range-wise.
From here on, only the 2.4 GHz PHY is being considered. The 16 channels (named 11..26) are non overlapping, have 2 MHz bandwidth and are spread 5 MHz apart.

3.4.1 MAC Layer

The one MAC behavior mode requires one PAN coordinator and can be extended with sub-coordinators that handle sub-portions of the network. The supported network topologies are star, cluster-tree and mesh. Two different channel access methods called beacon enabled (BE) mode and non-beacon enabled (NBE) mode.

The beacon enabled mode uses a super frame (figure 3.6), that begins with the beacon information, followed by Contention Access Period (CAP), optional Contention Free Period (FFP) and possibly an inactive period. The CAP uses slotted CSMA/CA, whereas the CFP uses TDMA as access method.

Inter Frame Spacing

Inter Frame Spacing (IFS) is the time between two MAC frames. 802.15.4e defines two different spacings, the LIFS and the SIFS inter frame spacings. They are expressed in number of PHY symbols (each symbol is 4 bits) and are therefore dependent on the transmission rate.

Long Inter Frame Spacing (LIFS) is used when the size of the PSDU is greater than 18 octets. It is defined as 40 PHY symbols (20 octets).

Short Inter Frame Spacing (SIFS) is used when the size of the PSDU is less or equal to 18 octets. It is defined as 12 PHY symbols (6 octets).

3.4.2 PHY Frame

The PHY takes the MAC frame and prepends it with some bits of data to form the Physical Protocol Data Unit (PPDU), before transmitting (figure 3.7). In total, 6 octets
are added by the PHY before transmitting, where the first 5 octets are the serialization header (SHR) consisting of 4 zeroed octets followed by 1 octet with bits 11100101, the next octet is Physical Header (PHR) where the first seven bits tells the length of the MAC frame (PHY Payload) [13].

![IEEE 802.15.4 physical protocol data unit](image)

Figure 3.7: IEEE 802.15.4 physical protocol data unit

### 3.4.3 802.15.4e

IEEE 802.15.4e defines five new MAC behavior modes, where three of them are aimed at real-time communication [7] [8] [9]. Each of the modes defines their own super frame structure, not compatible with the original 802.15.4 MAC mode.

**DSME**

DSME - Deterministic Synchronous Multichannel Extension. The most complex of the new MAC modes. It is suitable for multi-hop and mesh networks with deterministic (but not very low) latency. It supports channel hopping and channel adaption, the former changes channel according a predefined static scheme to decrease effects of interference, the latter chooses channel according to perceived channel quality in order to better handle interference. DSME is able to quickly adapt to time-varying traffic and changes in the network topology.

**TSCH**

TSCH - Time Slotted Channel Hopping. Supports multi-hop and multi-channel with TDMA access method. Allows multiple parallel communications in the network to take place simultaneously, by separating transmissions not only by time but also by channel.

Uses CSMA/CA retransmission algorithm to avoid repeated retransmissions.

**LLDN**

LLDN - Low Latency Deterministic Networks. Designed for low and deterministic latency, with high reliability. A specific goal of the design is to allow transmission of data from 20 different sensor nodes every 10 ms. Each network uses a single channel and the topology supported is star only. Acknowledgements of transmissions are optional.

The super frame changes according to the state of the network, depicted in figure 3.8:
The three states are:

1. **Discovery.** In this state new nodes scans all channels for discovery beacons from the Pan coordinator and responds with a discovery response frame. After 256 seconds (by default) of no new nodes responding, the PAN coordinator switches into configuration state.

2. **Configuration.** When nodes receive configuration beacon from the PAN coordinator they respond with a configuration status frame which contains information about the node and its requirements. After receiving a configuration respond frame from a node the PAN coordinator transmits a configuration request frame to the same node which responds with an acknowledge frame.

3. **Online.** In this state the super frame repeats endlessly and contains besides the beacon, up-link and bidirectional slots, as well as optional management time slots. Acknowledgement of down-link data, if used, uses an Acknowledgement Frame that is transmitted in the same bidirectional slot in the next super frame.

Note that all communication between coordinator and end nodes always occur inside a super frame which is always initiated by the PAN coordinator.

All time slots in a super frame are of equal length and therefore the super frame duration equals the number of time slots times the MAC frame duration.

There are four types of MAC frames used (figure 3.9): Beacon, Data, Acknowledgement and MAC Command. The overhead due to MAC header (MHR) and MAC footer (MFR) is only 3 octets, if security is not enabled. With security, 1 to 15 more octets are added to the frame, depending on the security level. The MHR without security is a single octet, also called Frame Control, which describes the frame type, frame security and frame acknowledgement requirements. The remaining 2 octets are the frame checksum.

Up-link acknowledgements (from actuator to gateway), if used, are sent in the next super frame, using the same bi-directional time slot. This means that the update frequency for actuators when acknowledgement is enabled is cut in half, while the update frequency for sensors remain the same.
The format of the Beacon Frame without security is shown in figure 3.10.

The format of the Data Frame follows the format of the MAC frame in figure 3.9. The format of the Acknowledge Frame is shown in figure 3.11.

### 3.5 WiFi (IEEE 802.11)

IEEE 802.11 is a standard for wireless local area networks (WLAN). The standard defines the PHY and MAC layers and was conceived in 1997 (IEEE 802.11-1997).

In 1999, two new revisions of the standard, based on the original, was added: 802.11a and 802.11b. The most common version is the IEEE 802.11g.

<table>
<thead>
<tr>
<th>Version</th>
<th>Freq.</th>
<th>Mod.</th>
<th>Rate Max/avg</th>
<th>Bandw.</th>
<th>Range in/out</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>5 GHz</td>
<td>OFDM</td>
<td>54/22 Mb/s</td>
<td>22 MHz</td>
<td>?/120 m</td>
<td>1999</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4 GHz</td>
<td>DSSS</td>
<td>11/?? Mb/s</td>
<td>22 MHz</td>
<td>38/140 m</td>
<td>1999</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4 GHz</td>
<td>OFDM</td>
<td>54/22 Mb/s</td>
<td>22 MHz</td>
<td>38/140 m</td>
<td>2003</td>
</tr>
</tbody>
</table>

Table 3.3: Characteristics of IEEE 802.11 a,b,g

Ranges are typical values and depends heavily on types of antennas used and the environment.
In 2.4 GHz WiFi, up to 14 possible channels are available, but as channels are spaced 5 MHz apart and the channel width is 22 MHz, only 3 channels are available without overlap, normally chosen as 1, 6, 11 (US), or as 1, 7, 13 (Europe) [11].

3.5.1 MAC Layer

The MAC uses CSMA/CA (Carrier Sense and Collision Avoidance) exclusively to deal with multiple access to the network. This type of media access control scheme is good for maximizing the throughput, but there are no guarantees that collisions will not happen and there is no upper bound for the number of collisions possible. This means that access is not deterministic and the latency is not bounded.

There is no super frame in WiFi, MAC frames have the general format shown in figure 3.12 [12]:

![IEEE 802.11 MAC frame, general format](image)

Each frame begins with a MAC header (MHR), followed by variable sized payload data of 0..2312 octets and ends with a 4 octet checksum called Frame Check Sequence (FCS). Not all fields in the header are used in all situations, but the order is always the same. Fields always used are "Frame Control", "Duration / ID" and "Address 1". Three classes of MAC frames exist: Data, Management and Control. Data frames always use all fields of the general MAC frame format, while Management and Control frames omit some fields. Management and Data frames have a specific format that all sub types follow. The format of Control frames varies depending on sub type. The interesting frames in the context of low latency data transfer are shown in figure 3.13. The Beacon Frame is a type of Management Frame, data is sent in the Data Frame and acknowledgements (ACK) are transmitted in a Control Frame.
CHAPTER 3. THEORY

Figure 3.13: IEEE 802.11 MAC frame types: management, control and data

The optional fields of the Beacon Frame are called Information Elements (IE) and each uses a two octets header followed by variable length data as in figure 3.14.

Figure 3.14: IEEE 802.11 information element

**Inter Frame Spacing**

Inter Frame Spacing (IFS) is the time between two MAC frames. 802.11g defines four different spacings, of which two are of particular interest, the DIFS and the SIFS inter frame spacings.

Distributed Inter Frame Spacing (DIFS) is the time to wait before transmitting after medium has been detected idle. It is defined as 28 $\mu$s.

Short Inter Frame Spacing (SIFS) is the time to wait until transmitting a consecutive frame. It is defined as 10 $\mu$s.

**3.5.2 PHY Frame**

The PHY layer prepends the MAC frame with some bits of information before transmitting. The complete physical frame is called the Physical Protocol Data Unit (PPDU). 802.11b standard introduced a shorter format of this frame and 802.11g uses the short
format exclusively. The short PPDU is shown in figure 3.15. The PLCP Preamble is 72 bits and transmitted at 1 Mb/s, it is followed by the PLCP Header of 48 bits, which is transmitted at 2 Mb/s and finally the PLCP Service Data Unit (PSDU) is transmitted at one of the supported rates (6,9,12,18,24,36,48,51 Mb/s). The PSDU is the OFDM modulated version of the MPDU, with some additional overhead in time of about 18 μs. The Preamble and Header transmits in 96 μs.

![Figure 3.15: IEEE 802.11 short physical protocol data unit](image)

### 3.5.3 RT-WiFi

RT-WiFi [6] is based on WiFi (IEEE 802.11) and modifies the MAC layer in order to support time slotted and deterministic access.

The real time network uses a star topology. The Beacon format of the original 802.11 MAC is maintained in a compatible way and Time Division Multiple Access (TDMA) is accomplished by placing the required super frame information inside a vendor specific Information Element (IE) (figure 3.16). This information includes length of time slots, length of super frame counted in time slots, and more.

![Figure 3.16: RT-WiFi information element](image)

As synchronization is needed between nodes to be able to schedule transmissions into time slots, each node maintains a 1 MHz timer which is periodically updated by timing information supplied in the Beacon Frame.

The format of the super frame is shown in figure 3.17.

![Figure 3.17: RT-WiFi super frame format](image)

Time slots are wide enough to allow not only a single transmission, but also an optional retransmission as well as an acknowledgement (figure 3.18).
CHAPTER 3. THEORY

Figure 3.18: RT-WiFi time slot format

Time slot durations can only take on values according to equation 3.1 [15].

\[
\text{SlotTimeMicros} = \left(64 \times 1024\right) / \left(2^n\right)
\]  

(3.1)

where \( n \) is the Slot length value in the Beacon Frame, with a currently supported range of \([0, 9]\).

The Data frame in figure 3.19 preserves the IPv4 and UDP headers.

Figure 3.19: RT-WiFi data frame format

ACK Frames use the same size and format as regular WiFi.

Coexistence with regular WiFi

As regular WiFi nodes are unaware of the real time extensions provided by RT-WiFi nodes, they will simply use contention based method (CSMA/CA) to access the channel, ignoring any time slots defined by the RT-WiFi super frame and thereby interfere heavily on the real time traffic. The situation can be improved by:

1. Making each regular WiFi transmission as short as possible, accomplished by using highest rates and limiting the Maximum Transmission Unit (MTU).
2. Shortening the Inter Frame Spacing (IFS) of RT-WiFi nodes, thereby giving them a better chance to access the channel compared to regular WiFi nodes.
3. Enabling the use of Clear Channel Assessment (CCA) in the RT-WiFi nodes, forcing them to delay transmission until channel is free from regular WiFi transmission.

Even with these solutions though, the problem of interference is not removed, only made smaller.
3.6 Channels in LR-WPAN and WiFi

Figure 3.20 shows LR-WPAN and WiFi channel allocation for the 2.4 GHz band.

As can be seen, four LR-WPAN channels (15,16,21,22) are not colliding with WiFi, unless WiFi uses non-standard channels.

3.6.1 Interference between WiFi and LR-WPAN

One single WiFi channel has a width that spans 4 LR-WPAN channels [11] and so 3 non-overlapping WiFi channels will occupy 12 LR-WPAN channels, leaving 4 LR-WPAN channels. However, interference on WiFi by LR-WPAN usually is negligible (as the LR-WPAN transmit power normally is magnitudes smaller), even if channels are close. Interference on LR-WPAN by WiFi is can be much more serious because of the often considerably higher transmit power of WiFi. Still, a center frequency offset of >7 MHz gives sufficient performance in most cases. [11]
Chapter 4

Analysis

The analysis focuses on two specific protocols, 802.15.4e/LLDN and 802.11g/RT-WiFi. LLDN and RT-WiFi meet the requirements on very low and deterministic latency for a relatively small number of nodes in a star topology network configuration.

4.1 Overview

LLDN and RT-WiFi presents two very different technologies for real time wireless networks.

LLDN with its relatively very low transmission rate of 250 Kb/s, makes up for the low rate by being a highly specialized for its job, using very small and simple control structures for minimal overhead. An advantage compared to RT-WiFi is the number of non overlapping channels available, 16 compared to 3. RT-WiFi on the other hand, has the advantage of extremely high rates (up to 200 times higher than 802.15.4).

4.2 Protocol configurations

This section describes the configuration of the protocols. Functionality like retransmission of data is not considered, as its usage would depend on non deterministic behavior of unreliable transmission. Security is neither considered, as it adds too much overhead in the case of LR-WPAN, but nevertheless it comes for free with RT-WiFi.

4.2.1 LLDN

The super frame format used in the analysis (figure 4.1) omits the optional management time slots as well as the retransmission time slots.

Figure 4.1: LLDN super frame used in analysis

The Group Acknowledgment (accumulative ACK to sensors) feature is not considered
useful in the analysis scenario and is therefore not used. The Beacon Frame in figure 4.2 then needs not to include the Group Ack field.

![LLDN Beacon Frame used in analysis](image)

Figure 4.2: LLDN beacon frame used in analysis

The data frames (figure 4.3) sent to sensors and from actuators use payload sizes between 2 and 32 octets.

![LLDN Data Frame used in analysis](image)

Figure 4.3: LLDN data frame used in analysis

Acknowledgement frames from actuators (figure 4.4), if used, are assumed to contain a single octet of payload. As this results in a frame size always smaller or equal to the beacon and data frames, the ACK frame has no influence on the final time slot size.

![LLDN Acknowledgement Frame used in analysis](image)

Figure 4.4: LLDN acknowledgement frame used in analysis

### 4.2.2 RT-WiFi

The analysis configuration will omit retransmissions and interference from regular WiFi is not considered. Figure 4.5 shows the time slot format. Definition for the *Guard Interval* has not been found at time of writing, but will both be assumed to be same as SIFS (10 micro seconds).
As retransmissions are omitted, the Ack Wait period is not used. The super frame in figure 4.6 consists of a Beacon time slot, a shared time slot and a number of data time slots.

The Beacon Frame is shown in figure 4.7. The SSID field is assumed to be of maximum length, 34 octets. The optional Information Elements are assumed to only contain RT-WiFi scheduling information.

4.3 Time slot and super frame duration

4.3.1 LLDN

To compute the time slot duration, the maximum size of MAC frames must be defined. Then, the Inter Frame Spacing (IFS) period (in octets) and the Physical frame header size is added. The time slot and super frame durations are calculated using the constants in table 4.1 and the variables in table 4.2.
### Table 4.1: LLDN time slot analysis constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYoverhead</td>
<td>6</td>
</tr>
<tr>
<td>SIFS</td>
<td>6</td>
</tr>
<tr>
<td>LIFS</td>
<td>20</td>
</tr>
<tr>
<td>BeaconFrameSize</td>
<td>8</td>
</tr>
<tr>
<td>DataFrameOverhead</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 4.2: LLDN time slot analysis variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DataFrameSize</td>
<td>$DataFrameOverhead + \text{PayloadSize}$</td>
</tr>
<tr>
<td>MACframeSize</td>
<td>$\max(\text{BeaconFrameSize}, DataFrameSize)$</td>
</tr>
<tr>
<td>IFS</td>
<td>if $\text{MACframeSize} &gt; 18$ then LIFS else SIFS</td>
</tr>
<tr>
<td>TimeSlotSize</td>
<td>$\text{PHYoverhead} + \text{MACframeSize} + IFS$</td>
</tr>
<tr>
<td>TimeSlotMillis</td>
<td>$\frac{\text{PHYoverhead} + \text{MACframeSize} + IFS}{\text{OctetRate}} \times 1000$</td>
</tr>
<tr>
<td>SuperFrameMillis</td>
<td>$\text{TimeSlotMillis} \times (1 + \text{NumSensors} + \text{NumActuators})$</td>
</tr>
</tbody>
</table>

### 4.3.2 RT-WiFi

The time slot duration is selected to be big enough to transmit either the Beacon Frame (including Guard Interval) or a Data + ACK frame combination (including Guard Interval and SIFS period). The Beacon Frame is 101 octets, including time slot information. The Data Frame is 62 octets, not counting the payload data after the UDP header. The additional time needed by the PHY to transmit the physical frame is then added. The final time slot duration is then rounded up towards nearest supported time slot duration. The time slot and super frame durations are calculated using the constants in table 4.3 and the variables in table 4.4.

### Table 4.3: RT-WiFi time slot analysis constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhyMicros</td>
<td>96</td>
</tr>
<tr>
<td>GuardMicros</td>
<td>10</td>
</tr>
<tr>
<td>SIFSmicros</td>
<td>10</td>
</tr>
<tr>
<td>BeaconFrameSize</td>
<td>101</td>
</tr>
<tr>
<td>AckFrameSize</td>
<td>14</td>
</tr>
<tr>
<td>DataFrameOverhead</td>
<td>62</td>
</tr>
</tbody>
</table>


Table 4.4: RT-WiFi time slot analysis variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AckFrameMicros</td>
<td>(\frac{AckFrameSize}{OctetRate} \times 1000000)</td>
</tr>
<tr>
<td>BeaconFrameMicros</td>
<td>(\frac{BeaconFrameSize}{OctetRate} \times 1000000)</td>
</tr>
<tr>
<td>DataFrameMicros</td>
<td>(\frac{(DataFrameOverhead + PayLoadSize)}{OctetRate} \times 1000000)</td>
</tr>
<tr>
<td>BeaconSlotMicros</td>
<td>(PhyMicros + GuardMicros + BeaconFrameMicros)</td>
</tr>
<tr>
<td>TxRxSlotMicros</td>
<td>(PhyMicros + GuardMicros + DataFrameMicros + SIFSmicros + AckFrameMicros)</td>
</tr>
<tr>
<td>TimeSlotMicros</td>
<td>(\text{max}(BeaconSlotMicros, TxRxSlotMicros))</td>
</tr>
<tr>
<td>TimeslotMicrosAligned</td>
<td>(2^{\text{ceil}(\log_2(\text{TimeSlotMicros}))})</td>
</tr>
<tr>
<td>SuperFrameMillis</td>
<td>(\text{TimeslotMicrosAligned} \times \frac{2^{\text{NumSensors} + \text{NumActuators}}}{1000})</td>
</tr>
</tbody>
</table>

4.4 Range versus power and rate

The network transmission range has a non linear dependency on the transmit power and rate. In general terms the dependency approximately follows the equation 4.1 [16] [17], where \(C\) is a constant dependent on the transmission medium and antennas used, \(\text{Power}\) is the transmission output power in Watts, \(\text{Rate}\) is the transmission rate in symbols per second.

\[
\text{Range} = C \times \sqrt{\frac{\text{Power}}{\text{Rate}}} \quad (4.1)
\]

What this means, is that quadrupling the power, doubles the range and quadrupling the rate, halves the range.

Now, inserting the range, rate and power values (for outdoors conditions) of IEEE 802.15.4 and 802.11g from tables 3.2 and 3.3 in Theory chapter, we get:

\[
\text{Range}_{802\text{11}g_m} = 34 \times \sqrt{\frac{\text{Power}_{mW}}{\text{Rate}_{Mbps}}} \\
\text{Range}_{802\text{15}4_m} = 38 \times \sqrt{\frac{\text{Power}_{mW}}{\text{Rate}_{Mbps}}}
\]

which are close enough that we can use a single final equation (4.2) for both:

\[
\text{Range}_m = 36 \times \sqrt{\frac{\text{Power}_{mW}}{\text{Rate}_{Mbps}}} \quad (4.2)
\]

Range for different values of power is plotted in figure 4.8.
Figure 4.8: 802.15.4 and 802.11g outside range vs power
4.5 Multi-star network

While LLDN has excellent range, the number of nodes that can be handled under low latency operation is limited. One way to improve the performance is to use multiple gateways, each controlling a smaller network of nodes. As long as the nodes per gateway is at least 10, the cost of adding wires to each gateway might still be acceptable.

Thanks to LLDN having 4 channels free from interference from WiFi (section 3.6), it is possible to make use of 4 channels simultaneously. The networks can then be arranged in two dimensions in a way that avoids internal interference between channels and can be extended indefinitely. Figure 4.9 shows the network arrangement. The transmit power should be tuned to best match the distance between gateways.

![Figure 4.9: Optimal channel arrangement for nearby WSANs in 2 dimensions](image)

RT-WiFi, only having 3 non overlapping channels, could still be used in similar multi-star network configuration, but in one single dimension only, where networks are placed along a line, using two alternating channels to avoid internal channel collisions.
Chapter 5

Results

This chapter presents plots of time slot and super frame durations, versus various parameters. The plots are based on formulas defined in the Analysis chapter.

5.1 Time slot and super frame durations

5.1.1 LLDN

Figure 5.1 shows time slot duration for different payload sizes. The rate is 250 Kb/s. The minimum duration of about 0.65 ms occurs for all payload sizes below 6 octets and increases proportionally with 0.03 ms per additional octet for larger payloads, until payload exceeds 15 octets where Long Inter Frame Spacing (LIFS) adds to the overhead.

![Figure 5.1: LLDN time slot duration vs payload size](image1)

Figure 5.1: LLDN time slot duration vs payload size

Figure 5.2 shows the super frame duration for different bit rates from 40 to 250 Kb/s. The payload size is 8 octets and the number of nodes is 20. The duration is directly proportional to the bit rate.

![Figure 5.2: LLDN super frame duration vs bit rate](image2)

Figure 5.2: LLDN super frame duration vs bit rate

29
Figure 5.3 shows the super frame duration for different number of nodes from 2 to 50. The rate is 250 Kb/s and the payload size is 8 octets. As can be seen, the duration is 10 ms for 12 nodes and 20 ms for 26 nodes.

![Figure 5.3: LLDN super frame duration vs nodes](image)

### 5.1.2 RT-WiFi

The RT-WiFi results show time slot and super frame durations both before and after time slot alignment.

Figure 5.4 shows time slot duration for different payload sizes from 2 to 32 octets. The rate is 6 Mb/s. As can be seen, the payload sizes in this range has very little effect on the resulting time slot duration, which stays quite constant at slightly below 0.2 ms. The reason for minimal changes in duration is because the payload data is very small relative to the total amount of data transferred within the time slot. Time slot alignment causes the final duration to be at a constant 256 $\mu$s until payload size hits 30 octets and duration doubles to 512 $\mu$s.

![Figure 5.4: RT-WiFi time slot duration vs payload](image)

Figure 5.5 shows the super frame duration for different bit rates from 1 to 54 Mb/s. The number of nodes is 20 and the payload size is 8. As can be seen, from about 12 Mb/s and up, the super frame duration changes very little and is kept at around 4 ms. Higher rates give very little decrease in duration because of the time-constant components built into the 802.11g standard, like physical serialization and preamble headers, as well as the inter frame spacing periods used. After time slot alignment is taken into consideration, the maximum useful rate is 6 Mb/s.

![Figure 5.5: RT-WiFi super frame duration vs bit rate](image)
Figure 5.5: RT-WiFi super frame duration vs bitrate

Figure 5.6 shows the super frame duration for different number of nodes. Number of nodes are varied from 2 to 50. Bit rate is 6 Mb/s and payload size is 8 octets. The super frame duration follows the number of nodes in a linear fashion. The duration is around 4 ms for 14 nodes and 8 ms for 30 nodes.

Figure 5.6: RT-WiFi super frame duration vs nodes
Chapter 6

Conclusions

LLDN (and IEEE 802.15.4 in general) offers exceptionally good range, while using relatively little power. LLDN being a low rate protocol has limitations on the number of nodes that can be part of a low latency network.

Future standards of IEEE 802.15.4 may incorporate higher rates such as 1 or 2 Mb/s, which would make a huge difference on the number sensors and actuators and the rate by which they can be updated. Some chips already support higher rates, like the AT86RF233 transceiver, by Atmel/Microchip [19].

RT-WiFi has acceptable range for most uses, but has much higher power demands. RT-WiFi also needs considerably more powerful hardware to run on. RT-WiFi being a high rate protocol, can serve more nodes at a given update frequency but also wastes away a lot of its rate advantage by using large data overheads. RT-WiFi currently has the additional disadvantage: it only exists for Linux. This means that the cost/size/power requirements will be considerably higher than for LLDN, as the sensor/actuator must have hardware integrated capable of running Linux. To be really useful as built into sensors and actuators, RT-WiFi would have to be ported to Off-The-Shelf WiFi-SoC’s.

Both protocols where analyzed, using a specific configuration. No retransmissions, no security for LLDN, 8 byte payload, 250 Kb/s rate for LLDN and 6 Mb/s rate for RT-WiFi (RT-WiFi can do higher rates, but with small payloads higher rates are just wasted).

At 100 Hz update frequency, LLDN can handle no more than 12 nodes. If acknowledge from actuators is required, this update frequency is halved for the actuators, while unaffected for the sensors.

At 100 Hz update frequency, RT-WiFi can handle 40 nodes. Acknowledge from actuators does not put a penalty on update frequency.

Interference-wise, LLDN (and LR-WPAN in general) has the advantage of many more channels to chose from, of which 4 are free from collision with RT-WiFi (and with WiFi in general). RT-WiFi on the other hand, has to deal with interference from other WiFi based networks.

Thanks to LLDN’s 4 interference-free channels it is possible to arrange multi-star networks with support for a higher number of nodes.
Chapter 7

Discussion

At the time of writing, faster rates (up to 2 Mb/s) for IEEE 802.15.4 (and therefore also LLDN) has recently been standardized [21] in the IEEE 802.15.4t-2017 standard. Already at 1 Mb/s, LLDN would be able to support at least as many nodes as RT-WiFi, at 100 Hz update frequency, assuming the higher rate is used over the entire transmission.

7.1 Power consumption

Power consumption, is not really part of the scope of the thesis, because of the assumption that actuator and sensors in the given problem scenario, would be powered by wires, to allow high update frequencies. Still, it might be useful to at least have an idea of the required power, even with wires attached.

Power consumption for IEEE 802.15.4 RF-SoC’s (by reading specifications of SoC’s JN516X, EM35x, CC2530, CC2730) lie in the lower range of tens of milliamperes while both transmitting and receiving with powers of 0 to 8 dBm (about 75 to 200 meters outside range at 250 Kb/s).

Power consumption for IEEE 802.11 RF-SoC’s (by reading specifications of SoC’s ESP8266 and ESP32) lie in the lower range of hundreds of milliamperes while transmitting (at 50% duty cycle!) with powers of 12 to 20 dBm (about 25 to 45 meters outside range at 6 Mb/s) and between 50 and 100 milliamperes while receiving.

Currents include both transceiver as well as the MCU running the protocol. The voltage supplies was between 3 and 3.3 Volts.

7.2 Existing implementations

RT-WiFi exists as Open Source implementation on GitHub [18]. The protocol is implemented as a Linux driver and so requires Linux capable hardware to run. Proprietary implementations I am not aware of.

Open Source LLDN implementations seems to be lacking at the moment, the only IEEE 802.15.4e protocol implementation I could find was openDSME, which only supports DSME. Proprietary implementations of (parts of) 802.15.4e do exist (Smart Mesh IP uses TSCH protocol), but LLDN implementations I have not found. Texas Instruments TI-15.4 stack is said to support 802.15.4e [20] but I have found no actual documentation on the e part that supports this.
Chapter 8

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Appendix A

Time plan

The thesis work was done according to the time plan in figure A.1.

Figure A.1: Time plan for the thesis work