Intra-Vehicle Connectivity

Case study and channel characterization

Albin Sellergren
Abstract

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The purpose of this thesis was to investigate the feasibility of a wireless architectural approach for intra-vehicle communications. The current wired architecture was compared to a wireless approach based on three prominent wireless protocols, namely Bluetooth Low-Energy, Ultra Wide-Band, and 60 GHz Millimeter wave technology. The evaluation was focused on their potential use within the intra-vehicle domain, and judged by characterizing properties such as frequency, bandwidth utilization, and power efficiency.

A theoretical study targeting the propagating behavior of electromagnetic waves was also involved. In particular, wireless behavior has been investigated both in general aspects as well as specifically aimed towards the intra-vehicle application. The theoretical study was then concluded and presented with a course of action regarding wireless connectivity. Beneficial design considerations, potentials and challenges were highlighted together with a discussion on the feasibility of a wireless architectural approach.

Suggestions for future work and research have been given, which include further expansion of targeted protocols, alleviating the restricted security aspects, and extend the physical aspects onto more software based approaches.
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Albin Sellergren
Uppsala University
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Keywords: Wireless Sensor Networks, Intra-Vehicle Connectivity, Bluetooth Low-Energy, Ultra Wide-Band, 60 GHz Millimeter Wave, Vehicular Network Architecture
Acknowledgements

First of all, I would like to thank Professor Christian Rohner, my supervisor at Uppsala University, for his dedicated support during this project. You have been a great source of inspiration throughout this project as well as in previous courses.

I would also like to thank Marcus Nordgren, Anna Funke, and Mattias Almljung, my supervisors at Semcon Gothenburg, for the continuous guidance and help along the way. It has been a great pleasure to work with such a inspirational company.

Finally, I would like to express my gratitude to all other friendly people at Uppsala University and my encouraging friends and family.

Albin Sellergren

Uppsala, June 2018
Populärvetenskaplig Sammanfattning

På senare tid har allt mer sofistikerade system introducerats inom bilindustrin. Sensorer som läser av vägförhållanden, mäter lufttryck, samt autonomt styr avancerade system inom fordonet. Denna utökade mängd sensorer i kombination med en stigande komplexitet i varje enskild enhet har skapat komplikationer i den nuvarande nätverksarkitekturen.


I detta projekt undersöks de möjligheter samt förutsättningar som finns till just trådlös kommunikation invändigt i fordon. En litteraturstudie har utförts där trådlös propagering samt elektromagnetiska vågors allmänna beteende har undersöks. En djupgående evaluering har sedan genomförts med syfte att realisera förutsättningarna i fordonet samt kartlägga de beteende denna specifika miljö skapar. En slutsats lyfts sedan fram där diskussion förs angående den fortsatta och mer fallspecifika evaluering som krävs för en bättre approximation. Det framkommer av arbetet att fordonet skapar goda förutsättningar för trådlös kommunikation där vitala parametrar såsom flat färdning samt Doppler påverkan visar sig relativt betydelselöse. Dessutom påvisas fördelaktiga protokoll såsom Ultra Wide-Band innehå goda naturliga förutsättningar mot den relativt svåra situation som associeras med fordon i form av hög elektromagnetisk utarmning samt trådlösa säkerhetsaspekter.
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### Acronyms

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<th><strong>Acronym</strong></th>
<th><strong>Description</strong></th>
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<tr>
<td>ADAS</td>
<td>Advanced Driver-Assistance System</td>
</tr>
<tr>
<td>AES</td>
<td>Advanced Encryption Standard</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic-Repeat-Request</td>
</tr>
<tr>
<td>ASR</td>
<td>Advertising Success Rate</td>
</tr>
<tr>
<td>AWGN</td>
<td>Average White Gaussian Noise</td>
</tr>
<tr>
<td>BLE</td>
<td>Bluetooth Low-Energy</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Density Function</td>
</tr>
<tr>
<td>CIR</td>
<td>Channel Impulse Response</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>CTF</td>
<td>Channel Transfer Function</td>
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<tr>
<td>DAA</td>
<td>Detect and Avoid</td>
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<tr>
<td>DPS</td>
<td>Doppler Power Spectrum</td>
</tr>
<tr>
<td>DS</td>
<td>Direct Sequence</td>
</tr>
<tr>
<td>EIRP</td>
<td>Equivalent Isotropic Radiated Power</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency-Hopping Spread Spectrum</td>
</tr>
<tr>
<td>GFSK</td>
<td>Gaussian Frequency Shift Keying</td>
</tr>
<tr>
<td>HDMI</td>
<td>High-Definition Multimedia Interface</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Symbol Interference</td>
</tr>
<tr>
<td>LDC</td>
<td>Low Duty-Cycle</td>
</tr>
<tr>
<td>LIN</td>
<td>Local Interconnect Network</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LTI</td>
<td>Linear Time-Invariant</td>
</tr>
<tr>
<td>LTV</td>
<td>Linear Time-Variant</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MB-OFDM</td>
<td>Multiband Orthogonal Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-Line-of-Sight</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>PDP</td>
<td>Power Delay Profile</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SIG</td>
<td>Special Interest Group</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>TH-BPAM</td>
<td>Time-Hopping Binary Pulse Amplitude Modulation</td>
</tr>
<tr>
<td>TPC</td>
<td>Transmit Power Control</td>
</tr>
<tr>
<td>US</td>
<td>Uncorrelated Scatterers</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide-Band</td>
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<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
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<tr>
<td>WSS</td>
<td>Wide-Sense Stationary</td>
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Introduction

The aim of this chapter is to provide a brief background to intra-vehicle connectivity, together with some of its current challenges. The potential of wireless connectivity is further introduced along with some of the most prominent aspects involved with wireless links in the vehicular domain. Thereafter, the objectives of this thesis is presented and motivated. The chapter continues with the restrictions and limitations of this project, and ends with an outline of the remaining chapters.

1.1 Background

Vehicles today are equipped with more and more sensors, such as sensors for detecting road conditions and driver’s fatigue, sensors for monitoring tire pressure and engine temperature, and advanced sensors for autonomous control. The increased amount of sensors in combination with growing complexity within each device contributes to difficulties regarding the intra-vehicle communication network architecture. Commonly used wired solutions such as the Local Interconnect Network (LIN) protocol, the Controller Area Network (CAN) protocol and the FlexRay protocol require a physical cable connection between associated sensors, actuators and electrical control units. Due to the increased sophistication of modern cars, a solely wired solution would add a significant amount of weight together with additional architectural complexity, affecting fuel consumption, overall maintenance, etc. Moreover, the installation of aftermarket sensors and functionality would be both inconvenient and difficult.

One way around this problem is to utilize the recent development in wireless sensor connectivity and networking technologies by relieving parts of the non-critical aspects of the current intra-vehicle networking from wired to wireless solutions. This would lead to a significant reduction in both deployment cost, fuel consumption due to reduced weight, and overall architectural complexity compared to the current networking approach. Additionally, the unburdened wired architecture enables further sophistication in terms of both internal interaction as well as external awareness.

The combination of optimized wired architecture and wireless interaction provides a internal communication platform where substantial driving enhancement can be obtained. In this way, sophisticated systems can forward
real-time information to drivers and surrounding vehicles about optimized
routs, traffic accidents, and other calamities. Meanwhile, decreased fuel
consumption, easier deployment and expanded future scalability would of-
fer substantial economical benefits not only for the individual customer, but
also for organizations involved in the vehicular domain. By providing this
flow of real-time information and thereby establish this swarm intelligence to
everything involved, vehicles can be transformed into coordinated and well-
formed assets without the increased architectural complexity involved in
the wired solution. Thereby providing drivers as well as passengers with an
information-rich travel experience while reducing the risks associated with
transportation.

This thesis aim to provide one of the first steps towards this development,
investigating both potential and challenges associated with wireless networks
and intra-vehicle connectivity.

1.2 Objectives

In order to investigate the feasibility of integrating wireless links into the
vehicular domain, it is vital to understand the radio propagation charac-
teristics in this specific environment as well as the physical behavior of the
emagnetic waves associated with wireless communication. The objec-
tive in this thesis is therefore to examine the possibilities associated with
wireless intra-vehicle connectivity. Constraints in terms of interference and
radio environments will be investigated in depth as well as possible beneficial
aspects obtained through an unburdened wired architecture.

A few contrasting wireless technologies will also be investigated solely based
on intra-vehicle applications. Critical characteristics such as frequency, reliabil-
ity, throughput, and overall costs will be considered when evaluating their
performance due to the enabled comparability with current wired architec-
ture. The chosen wireless technologies involve Bluetooth Low-Energy, Ultra
Wide-Band and 60 GHz Millimeter Wave due to their significance in recent
development as well as their diversity in key characteristics and functionality.

The project will revolve around two phases. An extensive analysis targeting
radio wave propagation in general, interference, and signal models together
with an investigation of the selected wireless technologies. This is followed
by a theoretical phase where studied physical behavior regarding radio wave
propagation associated with intra-vehicle connectivity will be further ana-
lyzed and focused exclusively on the vehicular application.

Finally, a suggested course of action regarding intra-vehicle connectivity will
be presented based on the research where potentials, challenges and critical
1.3 Limitations

Considering the extensive width of this project where radio wave propagation, wireless technologies, and vehicular communication solely based on individual aspects such as security, propagating behavior, or general channel modeling can be considered as major research topics by their own, a few limitations will be needed.

First of all, the wireless technologies will be analyzed based on their physical characteristics with a few exceptions in terms of security and compatibility. These aspects however, especially security in terms of vehicular applications, will be restricted since this topic extend the scope of this thesis.

Secondly, the proportions of the subject will act as a first insight towards intra-vehicle connectivity and can therefore be further expanded by targeting new wireless protocols, alleviate the restricted security aspects, and extend the physical aspects onto more software based approaches. By focusing on the fundamental characteristics associated with the vehicular domain, the goal is to provide a solid ground for future development.

In addition, the feasibility of various technologies will be limited in terms of material and case-specific options. Due to the complex nature of electromagnetic wave propagation, measures in order to mitigate the negative effects of interference and fading as well as potential enhancement to improve the wireless channel quality require more case-specific evaluation and extensive empirical studies. Since this paper will be exclusively based on a literature study from previous research, deviating result might occur due to the case specific nature of wireless systems.

1.4 Thesis Outline

The outline and overall structure of this thesis will be represented through the following chapters

- **Chapter 2 - Technical Background** - this chapter introduce the technical aspects associated with this thesis. The underlying motivation will be explained by presenting both current architectural approaches associated with the intra-vehicle network as well as the potential of wireless sensor networks.

- **Chapter 3 - The Wireless Channel** - the intention of this chapter is to expand the technical background towards the physical aspects
and propagating behavior of the wireless channel. Propagation of electromagnetic waves in general is explained together with mathematical representations and characteristic parameters associated with wireless channel behavior. The intention is to enable the reader to both theoretically and mathematically apprehend the evaluation of the intra-vehicle network in the following chapters.

- **Chapter 4 - Intra-Vehicle Analysis** - this chapter turns the attention of general wireless channels towards the intra-vehicle domain and analyze all fundamental aspects from both theoretical and mathematical points of view. This is where the main investigation of the wireless vehicular network takes place from both a general perspective as well as from the perspective of contrasting wireless technologies.

- **Chapter 5 - Conclusion** - the intention of this chapter is to discuss the feasibility of the selected wireless technologies by reviewing highlights from previous chapters and conclude the most prominent potential and challenges for the intra-vehicle channel.

- **Chapter 6 - Future Work** - finally, the intra-vehicle channel will be discussed through future directions and promising extensions of the conducted research. Different topics will be presented hopefully motivating forthcoming development.
2 Technical Background

This chapter aims to provide a brief introduction of the technical aspects involved in this thesis. Current architectural approaches associated with the intra-vehicle network will be provided together with a more historical perspective from which these new technologies have emerged. Additionally, the fundamental motivation of wireless sensor networks will be presented together with the wireless protocols chosen for this project.

2.1 Wired Architecture

Vehicles today are continuously growing in sophistication as new technologies emerge in order to enhance road safety and driving assistance, most of which are controlled by sophisticated embedded systems. As more features are added to the vehicles, the number of sensors and control units keeps increasing. Currently, almost all of the devices inside a vehicle connect through wired connections due to their low cost and reliable transmission. The increasing number of sensors leads to more wires that have to be added into the vehicles, raising the overall complexity of implementation as well as cost and ramifications for car manufacturers. The increased number of wires further contributes to the weight of the vehicles, thus influencing the continuous fuel consumption as well as limiting the range of possible positions for installing new sensors devices.

In the beginning when new sensors or electrical control units would be implemented, new point-to-point circuitry was added in a heterogeneous fashion. This approach however eventually lead to complex and inadmissible system architectures where communications where unnecessarily heavy and inefficient since the number of connections increased exponentially with the number of devices involved in the system. To overcome this problem, inter-connections were established connecting multiple devices to one another with bus-based networks such as Controller Area Network (CAN), Local Interconnect Network (LIN) and FlexRay [1].

All these network standards were specifically developed towards the automotive domain and typically used for control transmissions within the vehicle. The CAN protocol can be divided into two subcategories where systems requiring less bandwidth can employ CAN L due to its lower data rate but more
fault tolerant operation whereas CAN H can be used in more demanding applications. LIN was developed as an inexpensive and lightweight alternative to CAN used for simpler applications with lower requirement on bandwidth and timing such as door modules and mirror configuration. FlexRay on the other hand provided better flexibility through a higher maximum data rate and deterministic, time triggered behavior. These three standards are generally employed interchangeably where FlexRay handle more time critical and demanding systems while LIN and CAN maintain the less critical subsystems due to the less expenses involved in these protocols.

Recent years has seen another wired technology emerge in the form of Ethernet as a common architectural approach. Due to the growing sophistication of internal systems brought by the introduction of infotainment and demanding camera based driver assistance, protocols such as CAN and LIN no longer withstand the increasing demands of the internal traffic. Furthermore, with more awareness about fuel economy, on-board diagnostic systems, and network safety, more efficient and reliable communication networks are needed [2].

2.2 Wireless Sensor Networks

Wireless Sensor Networks (WSN) is a rapidly growing science within the field of digital communication. The main vision is to create smart environments that provide intelligence to applications through efficient and collaborative interaction. By utilizing wireless links, information can be transmitted between spatially distributed devices, commonly referred to as nodes, cooperatively working to offer a variety of monitoring and communicative applications without the extra weight of wires and increased complexity involved in circuitry design.

By maintaining a sophisticated flow of real-time information throughout wireless media, vehicles can be transformed into coordinated and well-informed assets where safety applications such as collision warning, driver fatigue, and cooperative merging can be established without the increased architectural complexity involved in the wired solution.

Furthermore, by relieving less critical systems within the vehicle to wireless approaches, resulting space can be occupied by more critical wired applications in order to mitigate the increasing complexity of new introduced systems. Less weight caused by integrating wireless links will provide a better fuel economy and enhance the communicative capabilities within the vehicle. It will also pave the way for supporting various applications provided by commercial products and cell phone integration such as location services, Internet access and route optimization.
Wireless intra-vehicle connectivity is a promising solution in order to alleviate the current constrained architecture via intelligent transmission control and network design, providing drivers as well as passengers with an information-rich travel experience, mitigating potential risks associated with transportation.

2.3 Selected Protocols

Interaction between different devices within a wireless sensor network must be done with a collective set of rules, procedures and formats in order to define the communication. Without this common ground, attempted interaction would only result in uninterpreted noise. The collection of rules and procedures related to a certain type of wireless standard is in radio transmissions referred to as a protocol. A typical radio technology consists of a stack of protocols where successive stages of the transmission are handled by different protocols. From the software based data management to the physical hardware and radio wave generation, contrasting applications depend on highly different ways of operation. In this section, an introduction of three protocols will be made focusing on their potential use within the intra-vehicle domain.

2.3.1 Bluetooth Low-Energy

Bluetooth Low Energy (BLE) is a short range communication technology developed by the Bluetooth Special Interest Group (SIG). BLE was introduced alongside the Bluetooth 4.0 specification in 2010 with the aim of achieving ultra-low power consumption and transmission efficiency, thus suited for applications associated with constrained devices and limited power sources. Systems based on BLE exhibit prolonged battery life as a direct outcome of the transmission efficiency, allowing devices to communicate for several months or even years on a single coin cell battery. With a data rate of 2 Mbps, BLE provide significant transmission capabilities in order to become a potential candidate for a range of wireless applications [3, 4].

In order to achieve such transmission efficiency, BLE utilize its own protocol stack ranging from the physical transmission modulation to complex software algorithms. In this thesis however, the focus lies exclusively on the physical aspects of the technology and the resulting channel characteristics it results in. The protocol consideration however will be based on a summation of the physical performance as well as attributes such as power efficiency and data rates corresponding to the utilization of the complete stack.

BLE operate in the 2.4 GHz Industrial, Scientific and Medical (ISM) band
2.3 Selected Protocols

with a spacing of 2 MHz divided between 40 channels. The output power lies in a range between -20 dBm and +10 dBm [5] which corresponds to a power of 0.01 to 10 mW. The modulation scheme used is Gaussian Frequency Shift Keying (GFSK), which in contrast to the standard FSK involve a Gaussian filter that smooth the transition between symbols, providing a increased tolerance against interference. The modulation provided by BLE together with the physical aspects of the technology result in a low-power and efficient transmission commonly used in wireless systems. BLE is one of the most prominent technologies in wireless consumer products and has been the subject of deployment in areas such as health care, home automation, industrial monitoring and indoor localization just to mention a few. Due to the continuous growth and widespread popularity, it is within the near future expected to be used in billions of devices [5].

BLE has thus been chosen as a viable candidate in this thesis representing the lower bound of the frequency spectrum. The low power and efficient transmission, together with the extensive employment throughout the wireless scientific community makes it a promising competitor in terms of in-vehicle connectivity due to the general understanding and wide selection of devices associated with this protocol.

2.3.2 Ultra Wide-Band

In order to accommodate the increasing need of faster transmission rates created by the growing sophistication of wireless systems, the attention has been brought towards another protocol known as Ultra Wide-Band (UWB). The name originates from the relatively large bandwidth in comparison to general transmission technologies such as Bluetooth or Wifi. By definition, any transmission that occupy a bandwidth of 500 MHz or more, and/or are using a bandwidth that is 20% or larger than the carrier frequency can be regarded as UWB [6].

UWB systems operate in an unlicensed frequency band ranging from 3.1 GHz to 10.6 GHz, thus share parts of the spectrum together with a majority of the world’s most common wireless technologies including Wifi. In order to efficiently utilize such a large bandwidth in cooperation with pre-existing communication systems without interfering, strict regulations has been placed upon UWB in terms of allowed transmission power. The resulting co-existence offer promising solutions where commercial technologies can be used in parallel without causing interference. Critical systems can thereby disregard scenarios where external wireless technologies might be brought into proximity of the target implementation. One highly correlated example of this involve the intra-vehicle environment where it is critical not to let commercial wireless products be able to significantly contribute to in-
ternal system interference.

The large characteristic bandwidth is established through short Gaussian pulses and its derivatives. The shorter the signal duration, the wider the resulting signal spectrum. By spending only a fraction of a nanosecond to generate the signals, less power is required, thus contributing to the low power consumption associated with UWB communications. Another significant contribution in terms of power management is the negligible carrier frequency. Depending on the selected modulation and transmission approach, data transmission can be done without the use of a carrier frequency since the bandwidth itself covers the frequency range in which a carrier frequency is generally used. Otherwise imperative and power consuming stages associated with signal generation such as frequency mixing and up/down sampling thereby become unnecessary. This further enable transmission without the need for highly sophisticated transceivers, resulting in low cost deployment and low power transmission [7].

The extensive spectrum provides flexibility in terms of range and transmission rate, where one desirable attribute can be enhanced at the cost of the other. Several contrasting applications have been established from this ability to move between low/high data rate and short/long range distance. In this thesis, the focus lies on the short range and high data rate application due to its relevance towards the target implementation. Transmission rates can with this configuration typically reach \( \pm 200 \) Mbps up to a range of 10 m [8], which favor the geometric configuration associated with the intra-vehicle environment.

The reason why UWB has been chosen as a viable candidate in this thesis can be realized from the various assets brought by the large bandwidth. By representing a major part of the intermediate frequency spectrum, UWB provide advantages such as high transmission rates, low cost, and resistance against interference. The possible co-existence with other wireless technologies further provides insurance against unpredictable events while allowing drivers and passengers to openly utilize wireless products without affecting the system integrity of the vehicle. More sophisticated systems such as advanced driver-assistance systems (ADAS), or demanding multimedia applications can in this way be available for implementation due to the possible rate of transmission.

2.3.3 60 GHz Millimeter Wave

The Millimeter Wave technology (mmWave) represents the uppermost candidate in terms of utilized frequency spectrum. The name arise from the characteristic wavelengths ranging from 1 to 10 mm, corresponding to a fre-
2.3 Selected Protocols

A frequency span of 30 GHz to 300 GHz [9]. One of the most commonly used radio technologies in this wide spectrum is the 59-64 GHz band, classified as the V-Band and commonly referred to as the 60 GHz unlicensed ISM band.

One of the key advantages of mmWave technology is the unprecedented transmission rate enabled by the wide desolated spectrum. Wireless links can reach transmission rates up to several Gbps, allowing highly sophisticated systems to share their data among each other in real-time.

Even though commercial use of this technology is relatively new, extensive research has resulted in a mature technology from decades of scientific and military applications [10]. Ranging from radio astronomy to flight radar system, a fundamental understanding of the propagating nature associated with mmWave technology has made it relatively straightforward to implement further into more commercial use.

Another great advantage of mmWaves is the possible spectrum utilization in small geographical areas. While more traditional radio technologies leave a relatively wide footprint throughout the frequency spectrum due to the traditional use of omnidirectional antennas, the small wavelength associated with mmWave transmission enable the use of directional narrow beams where all propagating energy is focused towards a certain direction. Thus allowing deployment of multiple independent wireless links in close proximity to each other without causing interference. The combination of controllable directional beams together with the poor penetration capability associated with small wavelength result in a possible secure operation.

As a pioneer in wireless fiber optics, mmWave technology helps pushing the limit of achievable transmission capacity in wireless sensor networks. With more data, the vehicles sensory system can optimize the driving strategy and internal control with a collection of complex and highly sophisticated sensor devices, operating and exchanging information in real-time. For this reason, mmWave technology has proven to be a valuable candidate and inspiring contestant for the intra-vehicle deployment.
The Wireless Channel

The intention of this chapter is to provide a technical background specifically directed towards the physical aspects and propagating behavior of the wireless channel. The aim is to provide sufficient knowledge of the underlying mechanics associated with electromagnetic waves in order to allow the reader to apprehend and reflect upon subsequent results in this thesis. A mathematical representation will be introduced explaining the most fundamental aspects of the wireless signal and thereafter altered progressively as more propagating phenomenon are presented. In this way, the reader will both theoretically and mathematically be able to acknowledge the elaboration which in turn will provide a solid ground when evaluating the intra-vehicle network in the next chapter.

3.1 Radio Wave Propagation

In contrast to the wired medium of access, wireless channels poses a severe challenge due to the complex set of environmental factors influencing the propagating signal. This section aim to provide a introduction to the most fundamental aspects involved during the communication between transmitter and receiver and how they affect the signal. The most significant difference between wired and wireless channels is the occurrence of multipath propagation. This corresponds to the existence of a multitude of propagation paths from transmitter and receiver, where the signal can be reflected, diffracted, or scattered along its way. In order to design an efficient network, it is critical to consider all these different propagation phenomena, and how they impact the channel.
3.1 Radio Wave Propagation

As seen in figure 3.1, path loss, multipath effects and signal blocking referred to as shadowing, impact the signal differently and with contrasting scale. In the following sections, these various phenomenon will be demonstrated from a more general perspective. The first important factor to consider is the natural attenuation of the signal referred to as path loss.

3.1.1 Path Loss

Consider a transmitted signal $s(t)$ with initial power $P_t$ at the transmitter and a corresponding received signal $r(t)$ with power $P_r$. The ratio between transmit power and receive power is defined as

$$P_L = \frac{P_t}{P_r}$$

which is known as linear path loss commonly defined as the value of the linear path loss in decibels:

$$P_L = 10 \log_{10} \left( \frac{P_t}{P_r} \right) dB$$

The most simplified version of this attenuation is known as the free-space propagation law. This law describes how a signal decreases in strength during propagation considering only a few parameters such as distance, frequency and individual gain at transmitter and receiver. The following equation describe the resulting received signal $r(t)$, of the transmitted lowpass signal $u(t)$.

$$r(t) = \text{Re} \left\{ \frac{\lambda \sqrt{G_t} e^{-j2\pi d/\lambda}}{4\pi d} u(t) e^{j2\pi f_c t} \right\}$$
where $\lambda$ is the wavelength, $f_c$ is the carrier frequency in which the signal propagates, and $d$ is the distance between transmitter and receiver. The distance traveled by the signal decide the resulting phase shift at the receiver which is reflected in $e^{-j2\pi d/\lambda}$. The variable $\sqrt{G_I}$ is for simplicity referred to as antenna gain, but corresponds to the product of the transmit and receive antenna field radiation patterns. This value depends on the type of antenna and the direction in which the waves are sent. Assuming the use of omnidirectional antennas, radiating the signal equally in all directions, the ratio between transmitted and received power can be view from (3.3) as

$$\frac{P_t}{P_r} = \left(\frac{\sqrt{G_I}\lambda}{4\pi d}\right)^2$$

The laws of energy conservation dictates that the integral of the power density over any closed surface surrounding the antenna must be equal to the initial transmitted power. The outcome corresponds to a power decrease with inverse proportion to the square distance between transmitter and receiver, assuming that the signal propagation is evenly distributed in all directions. The isotropic nature of the radiating electromagnetic waves this refers to thus provide a solid estimate for relatively short distances. Utilizing other antenna types however such as directional antennas, would provide a more concentrated transmission power, resulting in a decreased attenuation related to the distance.

Frequency also plays an important role in terms of attenuation over distance. The interpretation is given by its affiliation with wavelength $f = c/\lambda$, where increased frequency will result in decreased wavelength. While mathematically true, the increased path loss is a result of our definition of antenna gain rather than space somehow attenuating higher frequencies more. Due to the decreased wavelength corresponding to higher frequencies, smaller antennas are used when transmitting and receiving. As a result, a larger antenna is required in order to get the same gain at a lower frequency since the larger antenna will collect energy from a wider area. In other words, irradiance decreases with distance in accordance with the inverse-square law, regardless of frequency, but the impact is reflected in the attenuation and corresponding path loss.

Note that this model only corresponds to the most simplified open-space scenario and thereby limited to a path loss approximation for relatively short distances. Empirical studies have provided additional path loss models corresponding to a piecewise linear slope, thus expanding the simplified model to additional distances. One example of this found in [11] is defined as
3.1 Radio Wave Propagation

\[ P_r(d)dB = \begin{cases} 
P_t + K - 10\gamma_1\log_{10}(d/d_0) & d_0 \leq d \leq d_c \\
P_t + K - 10\gamma_1\log_{10}(d/d_0) - 10\gamma_2\log_{10}(d/d_c) & d > d_c 
\end{cases} \]

(3.5)

where the path loss exponents \( \gamma_1 \) and \( \gamma_2 \), \( K \), and \( d_c \) are empirically obtained values highly dependent on the environment. Similarities to the free-space propagation law can be found for short distances where the environmental factors doesn’t influence the signal significantly due to the open space, but extend the model with respect to the increased attenuation exponent for longer distances. The decline of 20 dB/decade provided by the simplified model turns to 40 dB/decade after a critical distance \( d_c \), which translates better to a practical scenario. Free space propagation is more of a theoretical or reference situation. In realistic propagation conditions, the transmitted wave is affected by various environmental factors which is better represented in this latter model. Different materials also have significantly different impact on the propagating signal when interacted with, which can be realized by the empirically produced relationship of

\[ P_r\ dBm = P_t\ dBm - P_L(d) - \sum_{i=1}^{N_f} FAF_i - \sum_{i=1}^{N_p} PAF_i \]

(3.6)

where \( FAF_i \) is the Floor Attenuation Factor and \( PAF_i \) is the Partition Attenuation Factor. Even though the equation is mainly aimed towards office buildings and indoor environments, the implication of an intra-vehicle application are evident based on the highly dependent values of the corresponding materials found in the associated table below [11].

<table>
<thead>
<tr>
<th>Partition type</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloth partition</td>
<td>1.4</td>
</tr>
<tr>
<td>Double plasterboard</td>
<td>3.4</td>
</tr>
<tr>
<td>Foil insulation</td>
<td>3.9</td>
</tr>
<tr>
<td>Concrete wall</td>
<td>13</td>
</tr>
<tr>
<td>Aluminum siding</td>
<td>20.4</td>
</tr>
<tr>
<td>All metal</td>
<td>26</td>
</tr>
</tbody>
</table>

A critical aspect in system design is therefore to consider how various materials affect path loss differently and how influential materials like metal can be. The direct proximity of metal associated with intra-vehicle environments thus provide a challenge in terms of system design. Prior to this however, further propagating mechanisms will be introduced in order to apprehend how the transmitted signal can be altered by its environment.
3.1.2 Diffraction

When propagating waves encounter geometrical irregularities such as sharp edges and dense corners, the interaction will cause the signal to bend if the dimension of the object is significantly larger relative to the wavelength of the signal. This phenomenon is known as diffraction. Accurate characterization of this behavior can be done by utilizing the geometrical theory of diffraction [12] but is most commonly modeled in wireless scenarios by the Fresnel knife-edge diffraction model due to its simplicity. The diffraction and the resulting bend causes the signal to be extended in distance on its way to the receiver as seen in figure 3.2.

\[
\text{Figure 3.2: Diffraction caused by intermediate object.}
\]

The increased travel distance give rise to both delays in time of \( \tau = \Delta d/c \) as well as phase shifts of \( \phi = 2\pi(d + d')/\lambda \) compared to the component traveling the direct path, known as Line-of-Sight (LOS). The received signal can in this sense be modeled as [11]

\[
r(t) = \text{Re}\left\{ L(v)\sqrt{G_l}u(t - \tau)e^{-j2\pi(d + d')/\lambda}e^{j2\pi f_c t} \right\}
\]

(3.7)

were \( L(v) \) is an approximation of the diffraction path loss relative to the LOS component and \( \sqrt{G_l} \) just as before corresponds to the antenna gain.

3.1.3 Reflection

Another phenomenon commonly experienced during signal propagation is reflection. When signals interact with various objects on its way to the receiver, different materials will cause the signal to respond in different ways, either through reflection where the signal bounces back from the surface or through transmission in which the signal penetrates through the material. The resulting power attenuation as well as the direction depends on the material properties, the incident angle, and the polarization of the wave. One way to illustrate the effect of reflection is through the so called two-ray model displayed in figure 3.3.
3.1 Radio Wave Propagation

Figure 3.3: The two-ray model illustrating a reflected wave. Source: Goldsmith [11]

Each wave in this model is represented by a ray following the direct path of propagation. As described by the name, this model include one LOS component representing the path from transmitter to receiver with distance \( l \), as well as one additional path reflected by the ground with a combined traveling distance of \( x + x' \). Equivalently as the diffractions impact on the signal, the reflected path will due to the extended propagation path result in a delay \( \tau = (x + x' - l)/c \), and phase shift \( \phi \), relative to the LOS component.

If we ignore the effect of surface wave attenuation, the combined received signal of the two-ray model can be defined as

\[
    r(t) = \text{Re} \left\{ \frac{\lambda}{4\pi} \left[ \frac{\sqrt{G_l}u(t)e^{-j2\pi l/\lambda}}{l} + \frac{R\sqrt{G_r}u(t-\tau)e^{-j2\pi(x+x')/\lambda}}{x + x'} \right] e^{-j2\pi f_c t} \right\}
\]  

(3.8)

where \( \sqrt{G_l} \) represent the combined antenna gain \( \sqrt{G_l} = \sqrt{G_a + G_b} \), \( R \) is the reflection coefficient, and \( \sqrt{G_r} \) is similar to the antenna gain a product of the combined gain corresponding to the reflected path \( \sqrt{G_r} = \sqrt{G_c + G_d} \). The reflected coefficient depend on the material properties and polarization which can be calculated from the Fresnel reflection coefficients for vertical polarization by

\[
    R_\parallel = \frac{\epsilon_r \cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\epsilon_r \cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}
\]  

(3.9)

where \( \epsilon_r \) is the complex relative permeability of the associated medium and \( \theta \) represent the angle of incidence relative to the normal of the surface. For horizontal polarization, the reflection coefficient is given by

\[
    R_\perp = \frac{\cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}
\]  

(3.10)

One important consequence of this phenomenon that can be interpret in equation (3.8) and further discussed in [11] is the resulting \( R \) for long distances. If the relationship between reflected and LOS component is approx-
3.1 Radio Wave Propagation

approximately the same, the angle \( \theta \) will approach 0, which in turn result in a reflection coefficient approaching \( -1 \). In this case, the reflected ray will be phase shifted into a inverted state, causing the superposition of each received component to destructively interfere with each other. This further press the fact that the simplified path loss model provides sufficient estimation for smaller distances while the critical distance explained in equation (3.5) provides the appropriate estimation for further distances due to propagation phenomenon such as reflection.

3.1.4 Scattering

Similarly to the transmitted signals resulting bounce on a smooth surface referred to as reflection, interaction with a rough surface will cause the signal to not only reflect, but also split into several smaller copies of the original signal. This phenomenon is called scattering and can be seen in figure 3.4.

![Figure 3.4: Scattering caused by irregular rough surface.](image)

The interaction between object and propagating signal once again causes the distorted copy to experience time delay \( \tau = (s + s' - l)/c \) relative to the LOS component as well as attenuation in power proportional to the product of \( s \) and \( s' \) [13]. The received signal can in this scenario be written as

\[
    r(t) = \text{Re} \left\{ u(t - \tau) \frac{\lambda \sqrt{G \sigma e^{-j2\pi(s+s')/\lambda}}}{(4\pi)^{3/2}ss'} e^{-j2\pi f_c t} \right\} \tag{3.11}
\]

where \( \sigma \) corresponds to the radar cross-section of the scattering object which highly depends on the roughness, size and shape of the surface. Depending on these shapes, the incident wave will spread out into many directions, making it challenging to approximate the effects in a deterministic manner.

3.1.5 Multipath Components

Interaction with multiple objects in the surrounding environment will as described result in reflected, diffracted, or scattered copies of the original signal. These copies are referred to as multipath components and can be attenuated in power, delayed in time, and shifted in both phase and frequency
compared to the LOS signal component. The outcome will be a distortion between the various components which in turn contribute to a variation in signal strength when added at the receiver. This phenomenon is referred to as *fading* which is a fundamental aspect in wireless signal behavior. Depending on each copy's individual phase and amplitude, the addition will be either constructive or destructive relative to the initial transmitted signal. Representations of both the transmitted and received signal can provide an understanding of this combined impact. First, let the transmitted signal $s(t)$, be represented as

$$ s(t) = \text{Re} \left\{ u(t)e^{j2\pi f_c(t)} \right\} $$

(3.12)

where $u(t)$ corresponds to the lowpass signal with bandwidth $B_s$, and $f_c$ is the carrier frequency in which the transmitted signal propagates. The received signal $r(t)$, can in this way be represented as

$$ r(t) = \text{Re} \left\{ \sum_{n=0}^{N(t)} \alpha_n(t)u(t-\tau_n(t))e^{j(2\pi f_c(t-\tau_n(t))+\phi_{Dn})} \right\} $$

(3.13)

where $n = 0$ corresponds to the first arriving LOS component. The summation represents the various multipath copies $N(t)$, influenced by distortion throughout the propagation, and thereby affected in amplitude $\alpha_n(t)$, Doppler phase shift $\phi_{Dn}$, and delayed in time $\tau_n(t)$. The Doppler shift is a phenomenon in which the frequency of the multipath components has been distorted to a certain degree depending on the angle of arrival at the receiver as well as the relative motion of the transmitter, receiver, and various objects influencing the propagation path. The change in frequency is generally relatively small, but since it affects all super-positioned components at the receiver, it becomes an important parameter to include.

### 3.2 Channel Modeling

In order to optimize wireless system design, a realistic channel model is appropriate. The aim is to reproduce the typical behavior of the channel constituted by the superposition of the propagation mechanisms described in the previous section. Modeling the wireless channel can prove challenging however due to the different complex contributions. Therefore, most models rely on a trade-off between accuracy and simplicity in which each model try to capture the aspects that are of most relevance to the wireless system behavior.

These can be classified as either *deterministic* or *stochastic* modeling approaches. The former focus on a representation of electromagnetic wave theory using Maxwell’s equations and ray tracing in which wave propagation is
based on geometric optics in combination with uniform theory of diffraction in order to provide simplified line models as seen in section 3.2.3 about reflection. It can also be referred to models based directly on empirically measured data. Favorable scenarios for this approach are therefore more site-specific applications where environmental factors remain static. Time variant and more dynamic systems on the other hand might prove difficult to determine due to the amount of physical aspects involved in the system behavior. The amount of measured data required to construct a sufficient system might also become cumbersome, in which stochastic models can prove useful.

Stochastic channel models are instead based on probability distributions and stochastic processes in order to represent the channel behavior. They are based on the assumption that the channel is influenced by a sufficient amount of unknown factors and objects in which it can be regarded as random.

Determining the system behavior is heavily based on how these parameters vary in time. The channel can be regarded as either time-variant or time-invariant, depending on the relative movement between transmitter, receiver and intermediate objects influencing the signal. Based on the classification, well-known system theory can be applied in terms of either Linear Time Variant (LTV) systems or Linear Time Invariant (LTI) systems [14]. Wireless channels are in general considered time variant, resulting in theoretically complex channel determination due to the increased amount of variables involved. If this relative movement is further regarded as random, the system functions can be described using stochastic processes. Fortunately, some wireless systems associated with more static deployment can be regarded as slowly time-variant, allowing many of the concepts associated with LTI-systems to be utilized with only a few minor modifications [15].

Assuming a LTV system, characterization is determined by the channel impulse response (CIR) \( h(t, \tau) \). Due to the multipath tendency described in the wireless channel, the CIR can be described as a superposition of multipath components and thereof expressed as a sum of time-shifted complex-weighted Diracs [11].

\[
h(t, \tau) = \sum_{n=0}^{N(t)} \alpha_n(t)e^{-j\phi_n(t)}\delta(t - \tau_n(t)) \tag{3.14}
\]

where \( h(t, \tau) \) represent time-variant impulse response at time \( \tau \) to an impulse at time \( t - \tau \), and \( \alpha_n(t) \) is the corresponding amplitude. Depending on the resulting signal resolution occurring at the receiver, the channel can be defined as either a narrowband fading channel or wideband fading channel. The former describes a channel where a significant amount of the multipath components arrive clustered (the delay spread is short relative to the
transmitted symbol duration). This will enable fast transmission rate due to
the reduced chance of different symbols arriving at the same time, causing
them to interfere with each other. The opposite will be the case in the wide-
band channel, where the expanded time of arrival causes different succeeding
symbol components to arrive on top of each other, resulting in interference.
Figure 3.5 illustrate this phenomenon where several multipath components
arrive with different delay and attenuation in power as a result of the various
propagation mechanisms.

![Figure 3.5: Multipath resolution caused by superposition of delayed signal components.](image)

In contrast to the static time invariant system, the impulse response of time
variant systems depend on two variables, the absolute time \( t \) and delay \( \tau \),
which result in Fourier transformation with respect to either one of them.
This in turn give rise to four important system representations associated
with these channels which all play fundamental roles in system characteri-
zation.

Tracing back to the impulse response, the relationship between the signal
input, \( x(t) \) and output, \( y(t) \), in time variant systems can be described as

\[
y(t) = \int_{-\infty}^{\infty} x(t - \tau) h(t, \tau) d\tau
\]

(3.15)

where \( x(t) \) represent the transmitted input signal, \( y(t) \) the received output
signal, and \( h(t, \tau) \) is the time-variant impulse response (CIR) of the channel.
The equivalent frequency domain representation is obtained by the Fourier
transform with respect to the delay time variable \( \tau \). The input-output rela-
tionship is given by

\[
y(t) = \int_{-\infty}^{\infty} X(f) H(t, f) e^{j2\pi ft} df
\]

(3.16)

where \( H(t, f) \) corresponds the time-variant transfer function (CTF). Another
system function can be derived by the Fourier transform with respect to the
3.2 Channel Modeling

Time variable \( t \), resulting in the Doppler-variant impulse response, also known as the spreading function, \( s(\nu, \tau) \)

\[
s(\nu, \tau) = \int_{-\infty}^{\infty} h(t, \tau)e^{-j2\pi\nu t} dt \quad (3.17)
\]

This function describes the spreading of the input signal in terms of delay and Doppler influence. In analogy to the impulse response and transfer function, the function can be transformed with respect to the variable \( \tau \), resulting in the Doppler-variant transfer function, \( B(\nu, f) \)

\[
B(\nu, f) = \int_{-\infty}^{\infty} s(\nu, \tau)e^{-j2\pi f \tau} d\tau \quad (3.18)
\]

These four different, but equivalent, representations act as the fundamental basis on which channel characterization is built. They are all highly related to each other due to their interweaving transformation structure.

One way of utilizing these functions is through their correlation towards each other [15], giving rise to new functions referred to as autocorrelation functions. Representing the correlation between a signal and a delayed copy of itself as a function of delay, these functions is commonly used in signal processing as a mathematical tool for finding repeating patterns, noise behavior, or identifying missing frequencies. For each system function, the corresponding correlation function can be calculated by ensemble averaging

\[
R_h(t, t'; \tau, \tau') = E\{h(t, \tau)h^*(t', \tau')\},
\]
\[
R_H(t, t'; f, f') = E\{H(t, f)H^*(t', f')\},
\]
\[
R_s(\nu, \nu'; \tau, \tau') = E\{s(\nu, \tau)s^*(\nu', \tau')\},
\]
\[
R_B(\nu, \nu'; f, f') = E\{B(\nu, f)B^*(\nu', f')\} \quad (3.19)
\]

where \( E\{\cdot\} \) represents the mathematical expectation and \( (\cdot)^* \) represents the complex conjugation operation. However, since the comparison in this way depend on four different variables, further assumptions might be appropriate in order to provide simplifications. Two frequently used assumptions are the Wide-Sense Stationary (WSS) and Uncorrelated Scatters (US) assumptions, referred to as WSSUS when combined. WSS act upon the assumption that the mean and covariance during small periods of time can be regarded as stationary, meaning they do not vary in time. This further implies that the autocorrelation function depend on the difference between two variables \( \Delta t = t - t' \) rather than each variable separately. In this sense, the dependency is based on the difference while different Doppler shifts can be regarded as uncorrelated [15]. Equivalently, US depend exclusively on the delay and act upon the assumption that the frequency correlation are no longer dependent on the particular frequencies, but rather on their frequency difference.
\( \Delta f = f - f' \). The name originates from the multipath components, or scatterers dependency, indicating that contrasting time delays can be regarded as uncorrelated. The four correlation functions can as an effect of this be written as

\[
\begin{align*}
R_h(t, t + \Delta t, \tau, \tau') &= P_h(\Delta t, \tau) \delta(\tau - \tau'), \\
R_H(t, t + \Delta t, f, f + \Delta f) &= R_H(\Delta t, \Delta f), \\
R_s(\nu, \nu', \tau, \tau') &= P_s(\nu, \tau) \delta(\nu - \nu') \delta(\tau - \tau'), \\
R_B(\nu, \nu', f, f + \Delta f) &= P_B(\nu, \Delta f) \delta(\nu - \nu')
\end{align*}
\]  
(3.20)

where \( P_h(\Delta t, \tau) \) is known as delay cross power spectral density, \( R_H(\Delta t, \Delta f) \) as time frequency correlation function, \( P_s(\nu, \tau) \) as scattering function, and \( P_B(\nu, \Delta f) \) as Doppler cross power spectral density. The reason why these simplifications are commonly used when characterizing wireless channels is the condensed parameters that can be obtained in combination with the fact that each correlation dependency has been reduced to only two variables. These single variable parameters are obtained by either setting one of the variables to zero, or by integrating over one of them.

### 3.2.1 Power Delay Profile

One of these parameters can be obtained from the complex impulse response \( h(t, \tau) \) as a result from \( P_h(\Delta t, \tau) \) by setting the time difference to zero or from integrating over \( \nu \) in \( P_s(\nu, \tau) \) \[11\]. The result is the delay power spectral density also known as the Power Delay Profile \( P_h(\tau) \).

\[
P_h(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} |h(t, \tau)|^2 \, dt
\]

(3.21)

The power delay profile (PDP) indicates the decay of multipath power with respect to the delay. The distortion is often referred to as the delay spread \( \sigma_\tau \), and defined as the time difference \( \tau \), between the first arriving LOS component (represented as the first peak in figure 3.6) and the last significant component based on a specific threshold. All components attenuated and distorted to a certain level will not provide significant contribution to the impulse response of the channel and is therefore neglected, the amount of time passed is referred to as the maximum excess delay \( \tau_{\text{max}} \).
3.2 Channel Modeling

Figure 3.6: The Power Delay Profile (PDP) represents the normalized received power relative to the delay. Several fundamental parameters can be extracted from the graph with reference to the first significant component.

The PDP describes the relationship between time, usually measured in nanoseconds, and intensity measured in decibel, of the multipath components relative to the first LOS component. Thus, channel characteristics can be quantified in terms of their dependence in time. Two commonly used parameters derived from the power delay profile is the average delay $\mu_\tau$, and RMS delay spread $\sigma_\tau$, defined as

$$\mu_\tau = \frac{\int_{-\infty}^{\infty} P_h(\tau) \tau \, d\tau}{\int_{-\infty}^{\infty} P_h(\tau) \, d\tau}$$

(3.22)

and

$$\sigma_\tau = \sqrt{\frac{\int_{-\infty}^{\infty} P_h(\tau) \tau^2 \, d\tau}{\int_{-\infty}^{\infty} P_h(\tau) \, d\tau} - \mu_\tau^2}$$

(3.23)

These parameters are referred to as time dispersion parameters and can be seen in figure 3.6. Note that each value represents the amount of time and power relative to the first arrived component. The RMS delay spread provides a good measure of how much a signal is spread over time which can be used to approximate the expected intersymbol-interference and thereby indicate the potential maximum transmission rate.

3.2.2 Coherence Bandwidth

Similar to the delay spread parameters ability to characterize the channel distortion in the time domain, the coherence bandwidth, $B_c$, can be used to characterize the distortion in the frequency domain. It describes the range of frequencies in which the components are amplitude correlated and thereby used as a statistical measure of the channel’s fading behavior. The coherence bandwidth can be obtained from the Fourier transformed PDP as seen in
3.2 Channel Modeling

The delay spread and coherence bandwidth are both through their inversely proportionate relationship commonly used parameters in order to describe the time dispersive nature of the channel. A large delay spread corresponds to a small coherence bandwidth.

Figure 3.7: Relationship between the power delay profile $P_h(\tau)$, rms delay spread $\sigma_\tau$, and coherence bandwidth $B_c$. Source: Goldsmith [11]

The correlation associated with the coherence bandwidth is typically based on a threshold of either 90% or 50% which corresponds to the following relationship between coherence bandwidth and RMS delay spread, defined by [16]

$$B_c = \frac{1}{50\sigma_\tau} \quad (3.24)$$

If the signal bandwidth is much less than the coherence bandwidth, the result will be a highly correlated fading across the entire channel, referred to as flat fading. This means that the fading will be roughly equal over the entire bandwidth. If the bandwidth is bigger than the coherence bandwidth on the other hand, the channel is referred to as frequency selective and thereby the fading variations will be highly independent across the bandwidth.

3.2.3 Doppler Power Spectrum

Similar to the power delay profile, the Doppler power spectral density $P_B(\nu)$, also known as Doppler Power Spectrum (DPS) can used to characterize the distribution of Doppler shifts at a given frequency. Representing the correlation between arriving components as a function of the frequency difference between them, this function can be derived by integrating the scattering function $P_s(\nu, \tau)$ over $\tau$. One important parameter derived from this function is the average Doppler shift

$$f_D = \frac{\int_{-\infty}^{\infty} P_B(\nu)\nu\,d\nu}{\int_{-\infty}^{\infty} P_B(\nu)\,d\nu} \quad (3.25)$$

The Doppler shift corresponds to the shift in frequency caused by the relative motion between transmitter and receiver. The magnitude is centered around
the carrier frequency $f_c$ of the propagating wave by $f_c \pm f_D$. Another important parameter derived from the Doppler spectrum is the RMS Doppler spread $B_D$, defined as the frequency range of which the power spectrum is nonzero and is used to measure the spectral widening of the signal over time.

$$B_D = \sqrt{\frac{\int_{-\infty}^{\infty} P_B(\nu) \nu^2 d\nu}{\int_{-\infty}^{\infty} P_B(\nu) d\nu}} - f_D^2$$

(3.26)

If the signal bandwidth is greater than the Doppler spread $B_s > B_D$, no significant influence will be involved on the received signal and can therefore be neglected.

### 3.2.4 Coherence Time

Equivalently to the delay spread and coherence bandwidths ability to describe the time dispersive nature of the channel, the Doppler spread, $B_D$, and coherence time, $T_c$, are used to describe the frequency dispersive nature of the channel. The coherence time describe the duration in which a propagating signal may be considered coherent in which the resulting impulse response remain consistent. If objects in the propagation path or at least one of the wireless stations move relatively fast, the resulting Doppler spread will be large and the coherence time small, which further result in a rapidly varying channel. The coherence time and Doppler spread are inversely related by

$$T_c = \frac{1}{B_D}$$

Figure 3.8: Relationship between the Doppler power spectrum $P_B(\Delta t)$, Doppler spread $B_D$, and coherence time $T_c$. Source: Goldsmith [11]

In analogy to the coherence bandwidth, common thresholds of 50% and 90% are used in order to measure the correlation.

### 3.3 Fading Models

As described earlier, the constructive and destructive interference caused by the arriving multipath components will cause fluctuations of the received signal strength. This phenomenon is referred to as fading and can be divided
into either *large-scale* or *small-scale* fading based on the spatial scale of the signal impact, described earlier as narrowband and wideband fading.

### 3.3.1 Large-Scale Fading

Large-scale fading describe the influence caused by factors such as path loss and shadowing effects associated with a relatively large area of the signal. These factors become more relevant with growing distance between transmitter and receiver as well as with their relative velocity against each other. Since the nodes associated with intra-vehicle connectivity is regarded as fixed however, large-scale fading is not expected to contribute significantly to the time variations of the received power.

### 3.3.2 Small-Scale Fading

Small-scale fading describe fluctuations in total signal strength caused by interference of the different multipath components. In general, this only corresponds to a few wavelengths. The time varying and frequency shifting nature can be described by the properties of delay spread, coherence bandwidth, Doppler spread, and coherence time.

A common approach in terms of small-scale fading characterization involve *flat fading* and *frequency selective fading*. The former occurs when a narrowband signal, corresponding to a small delay spread relative to the inverse signal bandwidth, \( \sigma_r \ll B_s^{-1} \), have a signal bandwidth significantly smaller than the coherence bandwidth \( B_s \ll B_c \). In this case, fading across the entire spectrum will have approximately the same gain and thereby contribute to a preserved spectrum. The fluctuating changes in time will thereby remain evenly distributed throughout the spectrum and provide an even, relatively flat, fading signal.

Frequency selective fading on the other hand occurs when the narrowband signal bandwidth is significantly bigger than the coherence bandwidth \( B_s >> B_c \). In contrast to flat fading, the smaller coherence bandwidth will provide separate varying components in terms of frequency, causing the signal to undergo individual fading throughout the spectrum. The selectively distributed fading dips might cause different succeeding symbols to interfere with one another, referred to as Intersymbol-interference.

Another approach of small-scale fading characterization involve *fast fading* and *slow fading*. This refers to a completely different phenomenon independent of the relative movement between transmitter, receiver, and interacting objects involved in the propagation. Instead, the focus lies on channel variations relative to the duration of a symbol. However, the exact definition of
fast and slow fading remains relatively obscure and thereby quite liberal in terms of individual interpretations. Thus, within the context of this thesis, fast fading refers to a constant coherence time of approximately $10^{-100}$ symbol durations, resulting in a channel with frequent variations in terms of fading. Slow fading on the other hand refers to a constant coherence time stretching over thousands of symbols and thereby provide a slowly varying channel in terms of fading.

Even though the different properties might appear quite similar, fast and slow fading differ from flat and frequency selective fading in terms of targeted fading aspect. A channel can either experience flat or frequency selected fading and fast or slow variations depending on the relationship between signal bandwidth and coherence bandwidth together with the duration in which the coherence time remain constant in terms of the number of symbols.

3.3.3 Stochastic Fading Distributions

As discussed in previous sections, the number of factors involved in wave propagation together with the numerous functions used to interpret the channel behavior might in some cases prove too complex to utilize in a deterministic fashion. Instead, some system considerations can be based on stochastic description methods and thereby based on stochastic processes and distributions. One of the most significant advantages with this approach, except from the reduced computational and theoretical effort acquired, is that the resulting fading statistics only depend on one single parameter, the average received power.

Two of the most commonly used distributions in wireless channels are Rayleigh and Rice distributions. The fundamental difference between the two is the absence of a dominant LOS component associated with the former.

The type of distribution can be interpreted from the probability density function (pdf), specifying the probability of a random variable falling within a particular range of values and the cumulative density function (cdf), specifying the probability of a random variable being less or equal to a certain value. A zero-mean Gaussian random variable has the pdf: [15]

$$pdf_x(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}$$  \hspace{1cm} (3.27)

where $\sigma^2$ is the variance. The probability density function associated with Rayleigh distribution can instead be written as

$$pdf_r(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \quad 0 \leq r < \infty$$  \hspace{1cm} (3.28)
where $r$ can be regarded as the amplitude of a random multi path component. Thus, the received signal power will provide a fading characteristic exponentially distributed with mean square value $2\sigma^2$ and variance $2\sigma^2 - \frac{\sigma^4}{2}$. The plotted pdf and cdf of a Rayleigh distribution can be seen in figure 3.9.

![Figure 3.9: power density function and cumulative density function of the Rayleigh distribution. Source: Wikipedia [17]](image)

The cdf of the Rayleigh distribution is obtained by integrating the pdf and thus correspond to

$$
cdf(r) = \int_{-\infty}^{r} pdf_r(r) \, dr = 1 - e^{-\frac{r^2}{2\sigma^2}}
$$

(3.29)

Rayleigh distributed fading characteristics provide an useful approximation for a large number of practical scenarios which has been confirmed by numerous practical measurements [15]. It can be used to describe a worst case scenario due to the absence of a dominant LOS component and thereby the possibility of large fading dips. It further remove the computational effort required for deterministic interpretation and can thereby provide a solid base for system design with a minimum amount of effort.

The Rice distribution on the other hand can be characterized by the dominant LOS component. The pdf associated with Rice distribution is given by

$$
pdf_r(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} \cdot I_0\left(\frac{rA}{\sigma^2}\right) \quad 0 \leq r < \infty
$$

(3.30)

where $I_0(x)$ is the so called modified Bessel function, $A$ is the amplitude of the dominant component, and $r$ corresponds to the Rice-distributed random variable. Thus, the received signal power will provide a fading characteristic exponentially distributed with mean square value $2\sigma^2 + A^2$. The ratio between the dominant component and the power associated with the distorted
component $A^2/(2\sigma^2)$, is called the Rice factor $K_r$.

The cdf of the Rice distribution is obtained by once again integrating the pdf which in this case corresponds to

$$
cdf(r) = \int_{-\infty}^{r} pdf_r(r)dr = 1 - Q_1\left(\frac{A}{\sigma}, \frac{r}{\sigma}\right) \quad (3.31)
$$

where $Q_1$ is the so called Marcum Q-function associated with the Bessel function included in the pdf.

The Rice distributions pdf and cdf can be seen in figure 3.10. Both Rayleigh and Rice distributions provide a good approximation of the fading characteristics and the ability to determine the appropriate distribution is relatively straightforward. By comparing the measured field strength values at the receiver and comparing it to the characteristics of Rayleigh and Rice, defining which distribution it regards can be relatively clear.

### 3.3.4 Noise

As a final note in this technical background, an introduction to noise is appropriate in order to provide a realistic scenario for wireless transmission. All phenomenon affecting the signal, whether it is the dominant LOS component or the various multipath components are all continuously influenced by one additional aspect, referred to as noise. In order to obtain a successful transmission, the ratio between transmitter and receiver (described in this chapter as path loss) is in practical scenarios referred to the useful ratio determined by the received strength of the signal in relation to the underlying noise present. This is called Signal-to-Noise ratio (SNR) and represent a critical parameter in wireless system design.
A commonly used channel assumption in terms of noise in wireless systems is the Additive White Gaussian Noise (AWGN) channel. This model targets the channel by simply adding a white noise process with constant spectral density and amplitude of Gaussian distribution to the transmitted signal. The result is a relatively simplistic model that neglects the influence of propagation mechanics and fading characteristics by adding an approximation of the final impact in terms of noise

\[ r(t) = s(t) + n(t) \] (3.32)

where \( r(t) \) is the resulting received signal, \( s(t) \) is the transmitted signal, and \( n(t) \) is the zero mean white Gaussian noise process with power spectral density of \( N_0/2 \).

There are several common sources capable of adding noise and provide interference associated with intra-vehicle environments. These can be classified as either external interference caused by external sources outside the vehicle, or internal interference caused by the internal mechanics of the vehicle.

### 3.3.5 External Interference

Rapid development in the field of wireless connectivity has as a direct consequence created a growing number of external factors with the ability to cause interference throughout the frequency spectrum. Surrounding cars, Vehicle-2-X technologies, distributed Wifi-deployment, and external wireless technologies like Bluetooth and cellular connectivity brought inside the car are just a few considerations in terms of external sources of interference.

The critical dependency of relative motion together with the unpredictable conditions of interference contributes to a complex web of possible approaches. As a consequence of this, empirical and statistical measures will be the course of action and thereby resolved later in this thesis during the intra-vehicle evaluation.

### 3.3.6 Internal Interference

Internal sources of interference provide a possible deterministic approach through its more static deployment and predictable behavior. Important environmental aspects like thermal noise and receiver noise can be isolated in terms of interference impact. Electromagnetic interference from engine and various electrical control units can be measured and adjusted based on the result.

Some internal sources correspond to highly time variant interference however and therefore require similar non-deterministic methods as in the external
case. Sources like man-made noise and vibrations correlated to the momentary velocity require a similar course of action due to the unpredictable nature.

With the help of the acquired channel models, system functions, and complementary parameters used for characterization, different networks can now be analyzed and evaluated on this basis. This will be the course throughout the next chapter where focus lies on the intra-vehicle applications associated with this thesis.
4

Intra-Vehicle Analysis

The intention of this chapter is to direct the acquired knowledge of the general wireless channel onto the intra-vehicle domain. A thorough analysis will be presented where all fundamental aspects will be discussed and presented from both theoretical and mathematical point of view. Additionally, the included protocols will be selected and subsequently used in order to investigate the vehicular approach from both general as well as protocol-specific perspective. The result is based on a literature study from similar measurement campaigns associated with wireless systems.

4.1 Protocol Feasibility

This section provides a brief analysis of the candidate protocols included in this thesis. Ranging from 2.4 to 60 GHz, the diverse physical aspects associated with each individual protocol will generate a contrasting outcome in terms of performance targeting intra-vehicle networks. Each protocols individual characteristic together with external factors such as cost, power efficiency and overall sustainability in this particular deployment will be the common nominator when regarding the best suitable choice. A short justification will be given for each investigated protocol followed by a extensive further analysis of the ones most suited for this particular application.

Bluetooth Low-Energy

Bluetooth Low-Energy (BLE) has proven itself to be a viable candidate in a wide range of wireless sensor applications. Despite the relatively low transmission rate, the power efficient nature of this protocol makes it a favorable technology. The immense popularity and widespread use however, also resembles the biggest disadvantage for intra-vehicle connectivity. The integration with cellular technology where a majority of today’s smart phones can be used together with other Bluetooth devices provides an opportunity in the number of users, but simultaneously creates a critical source of interference for the intra-vehicle application. The shared spectrum of the ISM-band has the potential of resulting in severe system failures due to coexistence problems where nearby devices has the potential to generate unpredictable sources of interference and thereby aggravate individual performance of each device [19].
Another concerning aspect related to BLE is the lacking transmission rate compared to UWB and Millimeter Wave. The rapidly growing number of sensors recently witnessed in intra-vehicle networks [20] together with the increased demand for sufficient transmission rate provide a difficult scenario where BLE struggle with the potential of sustainable development. Emerging vehicle technologies based on video links and artificial intelligence associated with high data rate transmissions simply prevent BLE in this regard by not being able to exceed required performance. However, due to the long history of overwhelming praise from the research community together with the widespread use of this technology, BLE will be subject for further investigation within this thesis. Additionally, by utilizing a specific frequency-hopping technique, where the transmitted carrier frequency rapidly changes in a pseudo-random pattern, BLE mitigate potential vulnerability against multipath tendencies in the channel. This ability establish a scenario where interference, internal security measures as well as tolerance against multipath behavior might be weighted as an advantage for this technology.

**Ultra Wide-Band**

One of the most fundamental advantage of UWB compared to conventional channels is the tolerance against destructive multipath effects and small-scale fading. This was left out of the presentation in the initial chapter in order to first introduce these propagation effects and familiarize with the overall subject matter. Further advantages can be derived from the famous Shannon-Hartley theorem [11], demonstrating that the capacity of the system can be improved either by increasing the channel bandwidth or the signal to noise ratio (SNR).

\[ C = B \cdot \log_2(1 + SNR) \] (4.1)

The characterizing wide bandwidth thus makes it possible to achieve high capacity channels, resulting in high transmission rates. UWB might therefore seem like an ideal candidate for the dense metallic surroundings and interference rich environment associated with intra-vehicle networks, but the extended bandwidth also contribute to some significant disadvantages. By utilizing a wide part of the frequency spectrum, the propagation processes, and thereby path loss and shadowing, becomes frequency-dependent. A direct consequence of this is the well-known WSSUS model not being applicable anymore [15]. Channel modeling and deterministic approaches thus becomes complex since a majority of the equations are based on frequency.

Another important drawback can be found in the number of available sensor devices and modules integrated with this technology. One potential cause can be realized by the faster and highly adopted versions of Wifi standards
which offer rates over the Gbps mark, while competing in the same frequency spectrum. Traditional indoor implementation of wireless networks doesn’t consider the critical aspects of low power, dense scattering and metal surroundings associated the intra-vehicle environment to the same extent. Therefore, open areas and available power sockets has drawn the attention away from UWB and resulted in a relatively scarce selection of available transceiver units.

Still, considering all aforementioned aspects of UWB, this technology gather some of the most influential assets related to the intra-vehicle domain and thereby remain a valuable candidate for this kind of application. Low cost, flexible transmission rate and system cooperation all provide promising impacts on the targeted system design. Aspects derived from the restricted power emission include security, low power consumption and jamming tolerance [8] which further validate its use within the safety critical nature of the automotive domain which will be further discussed later on in this thesis. Besides, the drawback of scarce device selection can be negated with the motivation that industrial implementation would benefit from a customization of transceiver units in order to optimize their performance in the intra-vehicle environment.

60 GHz Millimeter Wave

Millimeter Wave (mmWave) technology offer as previously stated unprecedented transmission rates compared to both BLE and UWB. The enhancement in transmission rates come at the price of power and implementation cost however. Both receiver and transmitter will contribute to significant power consumption in comparison to more traditional wireless technologies and each device will be costly due to the required structural complexity. Antenna design is considered to be one of the most challenging topics and an important motivator behind the continuous scientific research targeting this technology [9].

Nevertheless, critical assets in terms of high transmission rate, secure operation and directional beamforming represented by the mmWave technology still make it a compelling target depending on the application. Secure operation and capable transmission rates especially comes in mind when focusing on the intra-vehicle domain. The final decision can in this regard come down to the actual application within the car, whether the wireless link intends to carry extensive amount of data from a radar, or manage elementary transmissions associated with low-power devices. As mentioned in the introduction, more data will as a direct consequence allow more complex equations which can be condensed and transmitted to an intra-vehicle network that is "good enough" without the power draining properties of a potential internal
mmWave system. This is why this protocol won’t be the target for further investigation in this thesis, while still remaining a potential candidate for external implementation and Vehicle-to-X-applications [21].

4.2 Channel Model

Wave propagation and channel behavior in general is highly dependent on the specific environment, even in static conditions. Application specific models such as the intra-vehicle environment is characterized by many reflections and absorbing obstacles in contrast to indoor models where open space and less metallic surroundings is generally the case. Intra-vehicle channels therefore becomes difficult to describe with simple models such as free-space path loss or empirical indoor models because of the complexity given by the shape of the car, the contrasting materials as well as the propagating impacts provided by the road and the surrounding environment. It is desirable to apply various assumptions where the trade-off between simplification and accuracy must be weighed against each other. The choice of protocol further extends the resulting complexity. For example, narrowband channels such as Bluetooth can in many ways be simplified with the help of the WSSUS model described in section 3.3. This however, cannot be done when utilizing the UWB protocol due to the wide bandwidth and frequency selective behavior [6].

Fortunately, there are assumptions that can be made for the general channel inside the vehicle regardless of chosen protocol. One of these critical aspects is the variation and time dispersive nature associated with the propagating waves. Several studies has observed the intra-vehicle channel to be time-invariant, thus comparable to the general indoor channel assumption where Doppler effects and fluctuations in time has a relatively low impact. Time dispersive measurements [22], delay-Doppler evaluations [23], and general assumptions based on the static deployment of sensors involved during different measurement campaigns [24] all contribute to a collective approval that the intra-vehicle environment can be considered time-invariant. Thus providing a fundamental simplification regarding the determination of the wireless channel.

The following sections are intended to present the results of the intra-vehicle channel model with these general assumptions incorporated and based on the defining attributes described in chapter 3. Since the current sensors and applications in a vehicle are heterogeneous and the internal network configuration still remains relatively unspecified, the choice of wireless protocol will produce contrasting circumstances. In other words, depending on the final application, different requirements will be set in terms of delay, power consumption, security, multipath tolerance, etc. It might therefore be necessary
to evaluate more than one protocol in order to fulfill all requirements and further present a scenario where the final stance regarding optimal wireless technology is up to the reader.

Therefore, the following results will be focusing on the viability and overall performance based on both Bluetooth Low-Energy and Ultra Wide-Band due to the contrasting, yet highly promising attributes associated with these protocols. The intra-vehicle channel will also be presented from a general point of view targeting characterizing aspects present regardless of adopted protocol.

4.2.1 Multipath Behavior

One fundamental characterizing aspect of the intra-vehicle channel model involves the multipath tendency. A common approach is to interpret the behavior based on the system functions described in section 3.3. A series of empirical studies has been made with the common goal to determine the model for intra-vehicle networks. Niu et al. conducted a series of experiments where both narrowband and UWB technology was considered [22]. For narrowband channels, corresponding to Bluetooth among others, the multipath behavior can be described as the time invariant version of the channel impulse response (CIR) described in equation 3.14, the corresponding CIR can be defined as

\[ h(t) = \sum_{n=0}^{N} \alpha_n e^{j\phi_n} \delta(t - \tau_n) \] (4.2)

where \( N \) is the number of multipath components, \( \alpha_n(t) \) is the amplitude equivalent to the path gain, \( \phi_n \) is the phase shift, and \( \tau_n \) is the time delay of each multipath. For UWB channels on the other hand, the extensive bandwidth impact the statistical approach in terms of frequency selectivity. As realized by their mathematical representations, the propagation mechanisms described as diffraction, reflection and scattering will behave significantly different whether the target frequency is 3.1 GHz or 10.6 GHz. Thus, the narrowband assumptions will involve a relatively simplistic model compared to the wideband counterpart where flat fading and WSSUS no longer can be utilized. By adding a frequency dependent distortion factor to the definition, the UWB CIR can instead be more accurately be defined as

\[ h(t) = \sum_{n=0}^{N} \alpha_n \chi_n e^{j\phi_n} \delta(t - \tau_n) \] (4.3)

where \( \chi_n \) represent the distortion of the \( n^{th} \) multipath component. Further precision can be obtained by acknowledging the distribution of the arrival
time associated with each multipath component, which correspond to the
power density function described in section 3.4.3. For the UWB channel,
this can be described as a statistical Poisson process where the distribution
can be expressed as

$$pdf(\tau_n | \tau_{n-1}) = \lambda e^{-\lambda (\tau_n - \tau_{n-1})}, \quad k > 0,$$

(4.4)
The aforementioned analysis was conducted based on the intra-vehicle en-
vironment under the chassis which can be characterized by compact open
space, potential Line-of-Sight (LOS), and dense metallic surroundings. An
extended model has been made by several authors where the engine compart-
ment is included. In contrast to the relatively open space associated with
the previous model, the engine compartment replaces this property with a
dense cluster of metallic components in combination with a significant and
highly dependent source of vibration.

Jin et al. [25] among others have defined this rather harsh propagation from
a UWB perspective where multipath components tend to arrive in clusters.
The CIR can from this perspective be described as

$$h(t, \tau) = \sum_{m=0}^{M} \sum_{n=0}^{N} \alpha_{mn} e^{j\phi_{mn}} \delta(t - T_m - \tau_{mn})$$

(4.5)
where $M$ is the number of clusters, $N$ is the number of multipath components
within a cluster, $\alpha_{mn}$ is the amplitude of the $N^{th}$ component in the $n^{th}$
cluster and $\phi_{mn}$ is the equivalent phase shift. The time delay has been
modified in terms of cluster periods where $T_m$ represents the delay of the
$m^{th}$ cluster. This model is a recurring reference in intra-vehicle analyzes
defined as the Saleh-Valenzuela Model [26]. The distortion factor $\chi$ is for
simplicity neglected in this definition. Instead, an arrival rate is added to
the model defined as two Poisson processes in order to increase accuracy [24].
The resulting distributions is given by

$$pdf(T_m | T_{m-1}) = \Lambda e^{-\Lambda(T_m - T_{m-1})}, \quad m > 0,$$
$$pdf(\tau_{mn} | \tau_{(m-1)n}) = \lambda e^{-\lambda(\tau_{mn} - \tau_{(m-1)n})}, \quad n > 0,$$

(4.6)
In this model, $\Lambda$ represent the cluster arrival rate and $\lambda$ is the multipath ar-
ival rate within each cluster. The combined mathematical representations
thus provide a solid base of the characterization due to the parameters ob-
tained through each function. A pictorial version of the described behavior
can be seen in figure 4.1. Here the impact of the dense clusters associated
with the engine compartment can be realized from the different scales of
both the x-axis and y-axis in the time-amplitude curve.
4.2 Channel Model

Figure 4.1: The amplitude and CIR curves provided by the empirical studies of Niu et al. [22] The left side represent the engine compartment where dense scattering attenuate and distort the multipath components while the right side represent the relatively open space found under the chassis.

4.2.2 Power Delay Profile

Just as described in Chapter 3, several important parameters can be extracted with the help of the mathematical representations and the corresponding diagrams illustrated above. A series of studies has been conducted where similar results have been made in terms of characterizing model. Due to the complex nature of the geometrical environment however together with the various measurement approaches, different studies have reported slightly contrasting results. Most noteworthy deviation is the time dispersive parameters $\mu_\tau$ and $\sigma_\tau$ representing the average delay and RMS delay spread derived from the power delay profile.

Focusing on UWB, delay spreads ranging from 5 to 23 ns has been reported from different authors [27] where the probable cause can be traced back to the contrast in experimental setup and used equipment.

In the Bluetooth case, Liu et al. [28] found similar values of the delay spread ranging between 8-9 ns. The critical aspect of this deviating result and the main reason why it is elaborated here can be realized by the complexity of the intra-vehicle environment. A final network setup within the vehicle will therefore benefit from an application specific channel sounding where parameters like the delay spread can be determined and used to customize the transmission for optimized result. Therefore, measurement campaigns tend to focus on either average characterization of the time dispersion or statistical variations in time rather than specific parameter values.
4.2.3 Coherence Time

One of these aspects connected to the time dispersive nature of the channel is the coherence time $T_c$ presented in section 3.3.4. Moghimi et al. [29] conducted a series of experiments targeting the narrowband 2.4 GHz channel associated with Bluetooth where both stationary and driving scenarios were included. The result stated a minimum 50% coherence time of more than 2 seconds, demonstrating not only that the channel is slow-fading, but also that the impulse response can be considered constant over symbols as well as frames during transmission. The attentive reader might have noticed the absence of proper introduction for these more software based terms of symbols and frames in this thesis, the essential impact of this result however include overall simplicity in analysis, simulation and design of the system which further gives advantage to the transmission performance.

Less can be said about the coherence time viewed from the UWB perspective. As explained in section 3.3.4 the coherence time is together with the Doppler spread a measure of the frequency dispersive nature of the channel. The traditional narrowband signal experience equal amount of frequency shift with respect to the center frequency. Thereof providing a solid approximation generally used in order to interpret system behavior. However, the frequency selective nature associated with UWB caused by the wide bandwidth contribute to Doppler shifts and thereby time coherence approximations which significantly fails due to the selective frequency experience [23]. One potential approach in order to obtain time coherence values in the UWB case is to focus entirely on a modulation technique referred to as Multiband Orthogonal frequency-division multiplexing (MB-OFDM) where the wide band is divided into several sub-carriers of 500 MHz each [30]. In this way, a range of time coherence and Doppler shift values can be obtained from each corresponding sub-carrier and used to optimize the transmission. The approach can be considered irrelevant however realized by two important factors. First of all, the fact that the intra-vehicle channel has been widely regarded as time-invariant will cause Doppler shifts to provide insignificant contributions to the channel. Secondly, the proposed modulation (OFDM) used to determine these values undermine some of the most prominent advantages in the vehicular domain where resistance against multipath interference and robustness is replaced with increased transmission complexity.

4.2.4 Coherence Bandwidth

For the sake of including all characterizing parameters discussed in chapter 3 as well as endorse the legitimacy of the fading behavior stated above, the coherence bandwidth $B_c$ will be presented as well. In analogy to the slow fading behavior realized by the Bluetooth coherence time values, sev-
eral measurement campaigns have been conducted targeting the coherence bandwidth. A major conclusion made by Moghimi et al. [29] reported a coherence bandwidth of several MHz, thereby larger than the bandwidth needed for the narrowband transmission. The result once again predict a relatively simplistic channel model where the entire frequency spectrum will be coherently affected, previously referred to as flat-fading which simultaneously validate the frequency selective behavior associated with the UWB channel caused by the relatively wide frequency band.

### 4.2.5 Path Loss

Each transmission protocol will be heavily judged by its corresponding path loss in the vehicular domain. It is important however to distinguish between different type of path loss phenomenons and the specific application intended. For example, as realized by each equation given to describe the propagation of a wireless channel as well as the empirically produced path loss models, the wavelength and thereby the frequency play a fundamental role in terms of both distance and penetration capabilities. In this sense, Bluetooth tend to be superior to UWB when it comes to both these aspects provided by the lower frequency, especially considering the power regulations associated with UWB transmissions, which limits the obtainable distance to a maximum of 10m. In order to justify this rather unfair view of path loss however, praise must be given UWB in terms of multipath resistance and interference tolerance where the wide spectrum associated with this protocol simply outperforms narrowband channels.

A good example of this was given by Tsuboi et al. [31] and the result can be seen in figure 4.2. In this study, the difference between UWB and narrowband channels was measured throughout a series of experiment targeting the relative path loss between the two inside a vehicle. Two main scenarios was established where both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) was considered. Note that the narrowband signal was based around a carrier frequency as high as 6.85 GHz, thus focusing entirely on the difference caused by relative bandwidth and removing the penetrating performance caused by the lower frequency of 2.4 GHz associated with Bluetooth.
Judging by figure 4.2, the multipath resistance becomes clear in both LOS and NLOS scenarios where signal levels of UWB in LOS is stable with less than 8 dB fading depths while the narrow equivalent reaches as much as 40 dB fading depths together with very unstable signal levels for both scenarios. This proves the unique advantage given by the wide bandwidth in terms of multipath resistance highly correlated to the intra-vehicle environment. It is important to press the complexity in terms of path loss given by these highly dependent circumstances.

Less can be said considering applications where the wireless signal has to traverse through the exterior of the vehicle. Ghamari et al. [32] conducted a series of experiments where the target application involved a sensor integrated within the wheel and a corresponding receiver located within the vehicle. Three types of frequencies was used where both 2.4 GHz Bluetooth and 3.4 - 4.8 GHz UWB were included as a comparison of the path loss and car body attenuation caused by the exterior transmission. Instead of the general path loss approach based on power levels and gain, the experiment focused on a qualitative estimation of the link performance where a packet rate of 80% was reported. The conclusion was that UWB experienced higher attenuation compared to the lower frequency counterparts involved.
When evaluating the path loss associated with the intra-vehicle domain, it is important to acknowledge the complexity and corresponding deviation in terms of reported result as previously stated. One example of this can be seen in figure 4.3 where six different path loss measurements has been made considering different scenarios. The result demonstrates that the assumption of time-invariant channel behavior in some causes might be inconclusive and impact the transmission. Realized by the first (top left) and last (bottom right) graph in figure 4.3, a stationary LOS scenario will provide significantly different conditions compared to a NLOS driving scenario when transmitting the signal. The result further indicate the potential impact provided by the presence of a driver, where contrasting results can be observed in both LOS and NLOS scenarios, solely by including a driver. Thereby disputing the authenticity of the channel variation over time and time-invariant assumption of the channel.

The conclusion however regarding the general path loss associated with the intra-vehicle environment involve significant path loss in 2.4 GHz NLOS transmissions where losses $> 80$ dB has been reported when the transmitter and the receiver are in different compartments [33] in contrast to the 30 - 40 dB lower values associated with the UWB technology [22].
4.2 Channel Model

4.2.6 Fading Distributions

In order to counter the complexity mentioned above, this next section embrace the statistical fading distributions described in section 3.4.3 applied on the intra-vehicle scenario. As previously mentioned, the heterogeneous nature and corresponding number of factors involved in the wireless propagation might in some cases prove too complex to interpret in a deterministic fashion. Instead, some measurement campaigns base their result on stochastic description methods in order to reduce the required computational and theoretical effort and still come up with a sufficient approximation of the channel behavior.

A distribution study was conducted by D’Errico et al. [34] focusing on the 2.4 GHz spectrum included several scenarios with alternated sensor placement. Different positions around the vehicle as well as internally provided a comprehensive picture of the channel behavior in terms of both LOS and NLOS scenarios. As discussed in the technical background, the fundamental difference between Rice and Rayleigh distributions is the presence of a dominant component generally associated with LOS scenarios. Surprisingly, a majority of the 2.4 GHz measurements reported a Rice distribution even though the conditions were based on NLOS. The behavior can be seen in figure 4.4 where transceiver positions such as bumper, doors, wheels, and inside the vehicle was included and compared to a best-fit approximation of each corresponding Rice factor $K_r = A^2/(2\sigma^2)$ from the Rice distribution.

![Figure 4.4: Distribution investigation performed by D’Errico et al. [34] where several spatial positions was included such as bumper (B1 & B3), doors (D2), wheels (W2), and inside the vehicle (BaC).](image)

The interpretation of this counterintuitive result can be realized by the dense scattering involved due to the metallic surroundings together with the ap-
proximately invariant channel behavior. The overwhelming presence of scattered propagation paths are combined at the receiver to create a dominant, essentially constant signal together with significantly smaller multipath components slightly distorted by various time-variant effects [29]. Thus, Bluetooth distributions can be approximated similar to the general indoor channel with small Doppler spreads, AWGN simplifications, and as previously stated long coherence time, to establish a straightforward channel model in the intra-vehicle domain.

When it comes to UWB signals, Niu et al. [22] conducted a series of studies targeting the expected differences between traditional distributions of narrowband NLOS channels and UWB channels. The author righteously claimed that the general indoor channel usually follows Rayleigh distribution on the presumption of NLOS and static conditions. Thus, due to the wide bandwidth associated with UWB channels, the time delay between each multipath component might have followed a contrasting pattern and as a result provided a smaller number of resolvable paths. In analogy to the required differences in CIR caused mainly by the opposed bandwidths, the study performed a comparison between the Rayleigh distribution and the similar log-normal distribution in order to detect a noticeable contrast in the distribution as well.

The log-normal distribution is used in wireless channel characterization in order to represent altogether random attenuation. Instead of focusing on the presence of a distinctive LOS component associated with Rice and Rayleigh distributions, this model targets the average path loss in dB and measure the performance based on the log mean value and standard deviation [11].

![Figure 4.5](image_url)  
*Figure 4.5: Distribution investigation performed by Niu et al. [22] where the path amplitude and intra-cluster amplitude CDF beneath the chassis (left) and inside the engine compartment (right) was investigated.*
It was found that the best-fit distribution curve exclusively pointed towards the log-normal distribution rather than Rayleigh, thus confirming the suspicion. The result imposes the importance of different models between narrowband and UWB channels when optimizing the transmission design. In general, UWB will experience a propagation phenomenon within the intra-vehicle environment with distinctive clusters arriving at a much higher rate compared to the narrowband channel while the power decay will be smaller. This will allow higher transmission rates due to the decreased potential of Inter-Symbol Interference (ISI).

4.2.7 Interference

Interference plays a critical role in the evaluation process of the Bluetooth and UWB implementation. As discussed in the considerations regarding which protocol to choose, one of the main potential drawbacks with Bluetooth is the shared spectrum together with some of the most popular wireless technologies at the 2.4 GHz band. In this way, Bluetooth technology tends to be more exposed due to the widespread adoption in the wireless market. Lin et al. [19] conducted a series of experiments where this particular topic was investigated. In this study Bluetooth Low-Energy performance was evaluated under the influence of both Wifi and another Bluetooth device, all within the chassis of a commercial vehicle. The Bluetooth representation consisted of a wireless headset connected to a mobile phone while the Wifi representation consisted of a router connected to a laptop. The channel was also tested without any source of interference in order to provide a solid point of reference.

As previously mentioned, Bluetooth technology support adaptive frequency hopping schemes where interference can be mitigated by utilizing less constrained channels during transmission simply by jumping to another less constrained channel. An increased number of devices in close proximity to the transmission will contribute to higher risk of interference however due to the probability of occupying the same spectrum during frequency shifts. The reported results was based on the Goodput degradation, i.e. the number of successfully transmitted symbols, relative to the intra-vehicle transmission in the absence of external interference.
4.2 Channel Model

Figure 4.6: Interference investigation performed by Lin et al. [19] where interference from Bluetooth (BT) and Wifi was investigated in both driving and stationary scenarios.

As shown in figure 4.6, four different setups was investigated with alternating spatial relationships as well as both driving and stationary scenarios. The sources of interference were placed stationary in the cabin, which can be realized by the insignificant influence in the Engine to Engine setup. The author concluded that Bluetooth performed reasonably well under the interference of other Bluetooth devices while significantly degrading when exposed to Wifi interference. The explanation that followed pointed towards the underlying physical aspects of both interference sources in which Bluetooth as mentioned uses a particular "hopping-technique" while Wifi utilizes a spread spectrum modulation spanning over a much wider bandwidth. The consequence will be a more random case of interference where collisions occur when two Bluetooth devices hop onto the same channel, while experienced Wifi-interference becomes more determined.

A similar study focusing on the UWB technology was conducted by Chiana et al. [35]. This extensive analysis investigated the cooperative capability associated with UWB and evaluated the effects of interference both to and from narrowband systems. Even though the general case was considered rather than the intra-vehicle environment, all relevant modulation techniques was considered as well as contrasting channel profiles and receiver architectures, resulting in a comprehensive analysis. The author reported promising results where narrowband channels under the influence of UWB could be regarded as Gaussian noise in accordance to the general assumption. The regulations thus assure a co-existing state in which different narrowband protocols such as Bluetooth and Wifi can operate in close proximity without any significant interference. The author pressed however that unregulated use of UWB de-
vices might cause interference to narrowband systems in the possibility of a aggregated state where many sources of interference is present.

The study further reported some important issues on the reverse aspect concerning the narrowband systems influence on the UWB performance. It was shown that the impact strongly depended on numerous factors in the setup, such as modulation, receiver type, and carrier frequency of the interferer. While no significant degradation in the order of 20 dB or above was found, a scenario with strong narrowband interferers in close proximity to the UWB receiver could still impact the transmission when disregarding suitable design considerations. Fortunately, these considerations involve the alternative methods not promoted in the intra-vehicle implementation. In this specific case, it was shown that UWB systems can tolerate quite large levels of interference by narrowband sources, all different types of scenarios considered. The author pressed however that UWB implementation, while proving to be a promising communication protocol in co-existence with other wireless technologies, require careful analysis together with suitable countermeasures in order to establish an efficient operation.

4.3 Security
This section regard the security aspects associated with Bluetooth and UWB viewed from a physical layer perspective. It is important to note however that security solely targeting one of these technologies can be considered a science by its own due to the massive proportions associated with this topic when all layers are involved, thus extending the scope of this thesis. It is still a fundamental aspect in the evaluation process of the intra-vehicle environment however and will therefore be judged mainly based on the physical aspects associated with each technology. The section ends with a brief summary of potential justification earned from higher layer protocols.

4.3.1 Physical Layer Threats
Let us begin by introducing the potential threats associated with the physical layer in a general sense, which is divided into either jamming or tampering [36]. Jamming refers to an attack where spectral noise is created intended to partially or entirely disrupt the ongoing transmission. The severity and impact of the ongoing attack highly depend on the type of jamming approach as well as the ratio between cumulative noise and received signal. The various techniques can be divided into several sub-classifications

\footnote{The author suggested numerous advantageous considerations including coherent receivers, the carrier frequency of the interferer, the transmitted pulse shape, and the spreading code adopted during transmission.}
• **Spot jamming** refers to the most simplistic approach where the attacker directs all utilized noise power onto a single target-frequency. This kind of attack has the potential of causing severe network failures within narrowband channels due to the risk of compromising a majority of the spectrum used. Adaptive frequency hopping techniques utilized by Bluetooth technology helps mitigate the damage impact however.

• **Sweep jamming** on the other hand targets multiple consecutive frequencies in a quick sweeping pattern. The discontinuous target-frequency together with the unlikely synchronization with deployed transceivers generally makes this approach limited in terms of severity.

• **Barrage jamming** concurrently targets multiple frequencies in contrast to the quick sweeping mentioned above. The result is a wider range of frequencies compromised by the attack, but also less severity caused by the distributed power as a trade-off. The wider range of frequencies targeted, less power will be involved in each frequency, realized by the laws of preserved energy discussed in section 3.2.1.

• **Deceptive jamming** utilizes the ongoing communication by fabricating false replies to existing transmission, thus occupying the available bandwidth and constraining the network with constant traffic. The attack can either target a single frequency or several frequencies in analogy to the approaches above.

Realized by the various jamming approaches, narrowband channels tend to be more vulnerable to these kinds of attacks due to the compromised bandwidth ratio relative to UWB channels. There is however several countermeasures that can be used to mitigate potential risks. **Antenna polarization** can be used in a way where the mandatory correlation between two interacting sensors can alter their polarization upon the event of an external attack, thus interrupting the ongoing attempt. **Directional transmission** can be exploited, especially considering the screening capabilities involved with the vehicle chassis, where the transmission can be based on directional antennas rather than omni-directional, thus aggravating potential attacks. Frequency-Hopping Spread Spectrum (FHSS) is another countermeasure highly related to the Bluetooth technology. The carrier-frequency of the transmitted signals is repeatedly switched in a pseudo-random pattern as mentioned in section 4.1, thereby making the interception of a signal difficult. These are just a few passive design considerations against jamming attacks [37] that can be utilized in order to prevent or mitigate potential damage during transmission.

**Tampering** refers to attacks where a subset of sensors gets compromised through modification of the hardware. The tampered sensors thus pose a
threat through potential modified behavior or by being replaced by malicious sensors under the control of the attacker. Everything from counteracting the internal system functionality to extracting confidential data can be done once a network has been breached in this way. The intra-vehicle implementation fortunately provides a relatively straightforward countermeasure to this potential threat however where the highly sophisticated security mechanisms associated with the vehicle can be utilized. By deploying the network internally beneath the chassis, or by integrating sensors enough to obstruct exposure to attackers, the security measures could be enough to prevent potential attempts. Tampering will be an important aspect of aftermarket products where the integrity of the core functionality of the wireless network needs protection, while still allowing beneficial compatibility with various commercial products such as cell phone integration for infotainment purposes.

Considering the aforementioned threats on the wireless channel, both Bluetooth and UWB has been subject to substantial research in terms of the security and potential risks associated with various implementation scenarios. Brauer et al. [38] investigated the potential jamming of an outdoor Bluetooth based system. The jammer selectively targeted the advertising beacons used within BLE transceivers to initiate interaction between devices. The primary metric used within the experiment was the Advertising Success Rate (ASR) corresponding to the ratio between the number of successfully received BLE advertisements and the total number of transmitted advertisements. Another important metric included the area of effect in which the ASR was evaluated in terms of distance. The result can be seen in figure 4.7 where the ratio between ASR and distance is presented.

![Figure 4.7: The resulting ratio between Advertising Success Rate (ASR) and distance during selective jamming targeting Bluetooth Low-Energy. Experiment performed by Brauer et al.][38].

It was demonstrated that distances up to 5 meters can be exposed by jamming attacks enough to disturb the network while distances within 1 meter
4.3 Security

severely block the transmission. The report thus demonstrates the critical spatial aspects of deployment specific for BLE. Even though the counteracting frequency-hopping spread spectrum is considered efficient against jamming, the transmission is still as demonstrated vulnerable for attacks. Another major drawback that must be considered is the presumption of the attacker’s knowledge of the situation. Adaptive frequency-hopping can only provide jamming resistance as long as the pseudo-random hopping scheme remain confidential [39]. There is however cryptographic measures available where encrypted channel sequences can be exchanged by the network in advance in order to further mitigate potential threat. The trade-off however corresponds to an increased complexity during transmission leading to less bandwidth and increased power consumption.

Another widely regarded countermeasure against jamming attacks is to utilize UWB technology. This transmission protocol is in other words by itself considered a viable measure against attacks targeting the physical layer. This can be realized by the fundamental properties of UWB where each signal is distributed throughout a wide spectrum, resulting in a low power spectral density. The interception of the signal therefore becomes difficult due to the extensive range of the target-area. The same aspects that define the characteristic resistance against multipath propagation thus provide a countermeasure against potential attacks.

Several studies have been conducted targeting the UWB performance and physical layer security associated with jamming attacks. The combined studies performed by Hamalainen et al. [40, 41] investigated the impact and evaluated the performance on different modulation schemes in the presence of jamming. It was shown that strategic considerations regarding modulation, pulse derivative, and pulse width can help enhance the performance against physical layer attacks. Optimum result was reported utilizing a time-hopping scheme referred to as Time-Hopping Binary Pulse Amplitude Modulation (TH-BPAM) where general performance evaluation showed the Time Hopping techniques overall advantage over Direct Sequence (DS) modulation. The choice of pulse characteristics also proved significant where interference noticed by other wireless systems depended on this selection. In general, short pulses based on higher order Gaussian waveforms contribute to an increased transmission rate while interfering less with surrounding systems. Using longer pulses together with lower order waveforms on the other hand increase the overall tolerance against jamming.

Numerous possibilities enabled by the spectral properties of this protocol make it favorable for intra-vehicle implementation from a security perspective. The restrictions in power spectral density aggregate attacker’s chance of detecting the signal. The relatively large spectral bandwidth exploits the
benefits of different spread spectrum techniques where various trade-offs can be made in order to improve the jamming immunity as well as signal integrity [8]. Therefore, this protocol provides a natural protection against physical attacks and enables secured transmissions associated with low probability of both detection and interception.

### 4.3.2 Higher Layer Security

As mentioned in the introduction of this section, the outline of this thesis mainly focus on the security aspects associated with the physical layer in combination with modulation and mitigation techniques found in the lower layers. As a consequence, any justification found in higher layer security protocols are simply neglected, contributing to a rather unfair security perspective since encryption for securing information in wireless systems is in general done at the software based higher layers with powerful ciphers. However, this paragraph aim to provide some justification by briefly mention potential drawbacks and advantages associated with each protocol from a higher layer security perspective.

UWB is as previously mentioned defined by its physical attributes corresponding to the hardware based physical layer and the Medium Access Control (MAC) layer, thereby excluding any form of higher layer definitions. Any form of customized security protocols or optimized cryptographic approaches towards UWB transmission doesn’t currently exists as a consequence of this whereas it enables a certain freedom regarding higher layer protocol choices. A common approach adopted by UWB is the advanced encryption standard (AES) block cipher with counter mode (CTR) [42]. AES is one of the most popular encryption ciphers used to ensure secrecy of the transmission and have widespread use within numerous different applications and protocols. Utilizing AES ciphers does however compromise transmission characteristics such as throughput, packet size, and overhead due to the included cipher.

UWB communication systems have recently attracted considerable attention due to the increased momentum within the research community as well as the growing market. Another reason can be realized by the potential security found within the physical layers where robust transmission can be found naturally within the wide utilized spectrum while consuming minimal power. Various spread-spectrum techniques can as a direct impact by these attributes be employed on UWB transmissions to achieve low probability of both intercept and detection at the physical layer, while still being encrypted with a powerful cipher in order to enhance the safety. In this way, the transmission will not only be hard to detect and intercept, if potentially compromised the signal will still be difficult to decipher and exploit.
When it comes to BLE, the protocol architecture doesn’t follow the traditional layered structure such as the OSI model, TCP/IP model or any other known model. Instead, this technology comprise of a more individual architecture with highly defined and customized aspects stretching from hardware to software based layers, while still compatible with more general protocols. [43]

The widespread use and long history of Bluetooth has as a direct consequence contributed to that devices are traditionally subject to a large number of security threats and attacks. As a protection, Bluetooth continuously introduce new diverse security features and protocols in order to mitigate potentially serious attacks, focusing on all different security aspects including authentication, authorization and encryption.[44].

BLE define its security through two different modes with up to three levels of security. The first security mode corresponds to increasing levels of encryption whereas the second security mode is for different levels of data-signing protection where the transmitted data is "marked" with a digital signature. These security modes allow specification depending on the amount of security needed for a specific application. [5]. In this way, lightweight and non-critical applications can utilize a more relaxed secrecy mode with less complexity while more demanding applications can switch to higher levels of security in order to protect against eavesdroppers and ensure that authentication and confidentiality requirements are met. The current definitions consist of the following security modes:

- **Security Mode 1 Level 1**: refer to no security or nonsecure mode, where no security procedure is initiated. Typically used when no security is needed and transmission should maintain as lightweight and simple as possible.

- **Security Mode 1 Level 2**: involve unauthenticated pairing with encryption and is commonly used when data confidentiality is required whereas authentication is either unachievable or not required.

- **Security Mode 1 Level 3**: instead include authenticated pairing with encryption and used when data confidentiality and authentication are both required. This type of security level is both the strongest security mode and level.

- **Security Mode 2 Level 1**: refer to unauthenticated pairing with data signing and is commonly used when neither data confidentiality nor authentication is required.

- **Security Mode 2 Level 2**: on the other hand include authenticated
pairing with data signing which is used when data confidentiality is not required but authentication is required for the transmission.

Depending on the security mode used, a device can be classified into either trusted/untrusted, authenticated/unauthenticated, or unknown device. This classification will further govern the allowed transmissions associated with each device where the services are correspondingly divided into one of three available security levels. For example, authorization-level services can only be accessed by trusted devices, authentication-level services will require authentication, but no authorization, and therefore they remain inaccessible to the unauthenticated devices and unknown devices. Finally, the open services which are open to access and will be available to each device capable of receiving and processing the signal. However, untrusted or unknown devices do require authorization, before any type of access within the network will be granted. In this way, if the authorization fails, the access to any form of services will be denied.

It can be realized from the text that BLE offer a wide selection of contrasting modes and levels of security optimized for different applications. The choice corresponds to a trade-off between security and throughput which through the wide selection available can be highly customized to a specific application. Thus giving BLE a clear advantage over UWB higher layer security in the current state.

4.4 Protocol Performance

This section regard the individual performance associated with each device rather than the network as a whole. Discussions further targets the implied complexity associated with a majority of the parameters mentioned and press the importance of justification once the intended network has been set.

4.4.1 Power Efficiency

Wireless sensor networks are in many ways defined by the low power and constrained operation bounded by the limited processing capabilities and battery autonomy of the associated devices. That is why power consumption and resulting battery life plays a pivotal role in wireless network design. A common core in emerging wireless technologies is the ambition to provide low cost communication based on low power consumption. Determining the operational consumption of a network incorporate much more than just multiplying the number of sensors intended with the reported individual consumption however. There are several important factors to consider in order to provide the full picture. For example, thoughtful network considerations can help prevent unnecessary transmissions and over-emitting which contribute to an increased consumption, while strategic spatial deployment has
the potential of reducing the number of collisions during interaction, and customized sleep cycles can further decrease the internal consumption associated with each device.

A brief comparative study will be presented based on the power consumption of both BLE and UWB technology. Note however that conclusive results in the event of an actual implementation require justification due to the aforementioned reasons\(^2\). A good example in order to demonstrate the complexity of determining the actual power consumption can be realized by figure 4.8. Illustrating the typical operation of a BLE transmitter, the device will most likely go through several different states, such as receiving, sleeping, waking-up from sleep, etc. Even though the consumption in each individual state is known, the information is still insufficient in order to determine the total power consumed by the device. Further factors related to higher layers, security, propagation environment and switching between states must all be taken into account in order to get an accurate measurement of the total power consumed.

![Figure 4.8: The current consumption over time during Bluetooth Low-Energy operation (left) as well as current consumption over time during a single connection event (right) [46].](image)

The widespread use and long history of WSNs has enabled BLE to offer a diverse collection of devices customized towards the application and intended purpose. With a current consumption typically ranging from 6.1 – 27 mA and maximum output power between 1 – 3 mW [47], sensors can last for years. Even though the operational consumption will be highly dependent on the application, BLE provide a wide range of possible devices all associated with low consumption. More extensive information regarding power consumption in recent BLE devices can be found here [48]

UWB is in analogy with BLE associated with low power applications. The modest time-frame spent in order to generate signals contribute to low power

\(^2\)Solely counting the connection intervals which ranged from 0.1 to 16 seconds, the battery life estimation ranged from 37 days to 4506 days (12.3 years) on a CR2032 battery, realizing the immense dependency associated with power consumption [45]
consumption together with the negligible carrier frequency which further remove the otherwise imperative and power consuming stages associated with signal generation. The actual operational values are likewise BLE highly dependent on the intended application where potential trade-off can be found in terms of modulation, security, transceiver anatomy, etc. Available modules was however scarce during a long period of time which contributed to suboptimal design and performance. The relatively large circuit size and high cost was previously regarded as undesirable traits for UWB applications, making it undesirable compared to other wireless technologies. Recent advantage however has once again given momentum to this technology where the use of CMOS-Integrated Circuits resolved these previous issues because of their miniaturization, low cost and low power capabilities [49]. Thereof enabling complete single-chip solutions for UWB as well. Recent studies has provided low power devices ranging from 0.3 – 10 mW thanks to the improvement of CMOS technology.

As a conclusion, BLE tend to have better power consuming performance relative to UWB technology in the general sense, but including the normalized value into the equation present a separate result. From the mJ/Mb unit point of view, where energy consumption is presented in relation to the data transmitted, UWB have better efficiency by quite some margin. It is therefore important to value this parameter independently based on the intended application. Note however that even though power efficiency and battery life in general can be regarded as a valuable parameter to include. The in-vehicle application does not benefit from any prolonged battery life due to the impractical scenario of battery changes and extended vehicular service. Therefore, the deployment of wireless sensor networks within a vehicle can be considered to be connected to the existing distributed power network, thereby limiting the power efficiency parameter to more of a comparable factor towards eventual constraints on the network and battery.

4.4.2 Transmission Rate

It is surprisingly difficult to determine the current available transmission rate for UWB technology. The extensive bandwidth enables a lot of potential in terms of security, reliability, as well as transmission rate. First of all, the type of modulation impacts the possible rate immensely due to the contrasting behavior of each choice. Secondly, the recent momentum in the research community has created both frequent and continuous improvement where new chip solutions, both practical and theoretical, push the boundaries of several characterizing parameters associated with this technology, including the transmission rate. Ranging from the comparatively low rate of 6.8 Mbps provided by the Decawave DWM1000 chip, to the implemented high-rate low-power 500 Mbps solution [50], and stretching as far as sev-
eral Gbps when dedicated towards short-range communication [51]. UWB thus provide great potential in terms of achievable transmission rate without compromising the low power consumption.

BLE on the other hand has a set transmission rate of 2 Mbps defined in the already widely adopted Bluetooth 5.0 version from 2016. Even though this particular parameter significantly suffers in relation to UWB, the intended application may still prefer properties such as low power consumption and mobile integration, in which the Bluetooth technology prosper.

4.5 Implementation Factors

This section further present influential aspects and contrasting behavior provided by the two protocols, this time from a more industrial and implementation related point of view. Topics such as cost, current market, and standardization will be discussed together with the corresponding impact provided by each of these factors.

4.5.1 Cost

One critical aspect of network design is the cost and economical factors involved in the implementation. Several properties can be derived from this common core including power consumption, manufacturing, and overall complexity associated with each device, which all contribute to reduced cost associated with each individual unit. However, in analogy to the power consumption previously discussed, there are several important factors to consider in order to obtain a realistic perception of a potential implementation cost. Startup costs required to replace current technology must be weighed against potential benefits from switching. Reduced maintenance, increased scalability, and reduced fuel consumption are all beneficial factors provided by the wireless technology, while possible expenses might be found in increased security measures. The resulting complexity thus requisite an investigation of its own, but counting the impacts provided by wireless technology, the car industry do seem like a promising market for wireless technology in both short term and long term perspectives.

Bluetooth owe the current advantage in this category to the widespread use and overall popularity in both commercial use and attention within research communities. Units can be found starting from $2.38 with a wide collection of devices in similar price range specialized towards different applications [2]. Future prospects can also be considered a viable economical factor since more commercial products such as phones and laptops support BLE, resulting in a larger market. The impact includes more and more consumer devices supporting BLE in the near future, making it easier to enable new features
on vehicles with lower cost due to the prevalent market share.

In terms of UWB, the same momentum that reduced the size and complexity of this technology also helped reducing the overall price associated with each device. Companies like Decawave helped influence the market, shipping UWB solutions from $10 per unit for a few hundred units down to $3 per unit for higher-volume applications [52]. Therefore, Bluetooth possess advantage in terms of price and selection compared to UWB [2].

4.5.2 Market and Costumers

One key dependency regarding the adaptation of wireless technologies in the vehicular domain is the leading enterprises willingness to invest and dedicate their efforts towards a certain technology. Significant changes usually occur once a collective state of approvalment has been established in terms of reliability, improvement, and overall result.

In terms of UWBs previous struggle in the wireless market, new agreements was forged in the beginning of the 2010s between BMW, IBS and Ubisense, where deployment of a real-time Location Identification System (LIS) was made across the global vehicle manufacturers production facilities [53]. Since then, Ubisense has expanded further within the vehicle market to include customers such as Aston Martin, Audi, Magna, Mini and VW. Thereby actualizing the much needed collective agreement. The general application adopted by the market has been more aimed towards improvement in facilities and construction however and less towards actual intra-vehicle implementation. The recent attention within the research community has the potential on the other hand to direct the attention towards internal deployment as well.

In terms of available chip solutions and modules, DecaWave stands as one of the leading suppliers. They have been active in the standardization efforts since the earliest days and have a long list of resellers including Agilion, Bluflux, Ciholas, Idolink, OpenRTLS, Red Point, RTLS, Sewio, Wipelot, and Woxu [54]. Zebra Technologies is another noteworthy solution provider in the UWB space.

Bluetooth on the other hand has long lingered as a major player in the wireless market. A extensive history of popularity within commercial markets, industry, and research communities has provided a plethora of contrasting solutions, diagnostic tools and understanding, together with general appreciation. Leading embedded cooperation’s such as Texas Instruments, Atmel, Nordic, Renesas, Dialog, ST Microelectronics, and Cypress is just a few of the available vendors providing BLE chip solutions [48]. The history of Bluetooth undeniable contribute to a advantage in terms of selection and
general understanding when it comes to available solutions, which in turn can provide ease in potential deployment.

4.5.3 Standardization

This section regard one of the current drawbacks associated with UWB caused by the relatively turbulent history of this technology. The success and impact of new technologies are closely related to the development of interoperability standards and detailed definitions. Bluetooth for example was standardized by the IEEE as the 802.15.1 and has since then been maintained and further developed by the Bluetooth Special Interest Group. Standardization enables scientists and developers worldwide to utilize a technology through a preset of rules and definitions, thus allowing further development and investigation without starting from scratch every time and further allowing interoperability between different devices worldwide. It is easy to realize the advantage provided by standardization and the resulting benefits achieved through a collective and predefined set of rules.

The history of UWB standardization in terms of communication systems has unfortunately been influenced by conflict, competition, and industrial differences which have affected the standardization of this wireless technology. One attempt to standardize UWB was done in 2003 by the IEEE 802.15.3a task group, this was however withdrawn later in 2006 since the members were not able to come to an agreement choosing between two technology proposals [55]. The consequence was that the task group was disbanded and the chance of UWB to make a presence in the consumer market was temporarily blocked. One of the competing technology proposals was later included into another standard called ECMA-368, namely the UWB Multiband approach.

This international standard specified the physical layer and medium access control layer of UWB aimed towards a high-speed, short-range wireless networks. The targeted frequency spectrum was including all or part of the spectrum between 3.1 GHz to 10.6 GHz which as a result achieved data rates of up to 480 Mbps. Another standard defined by the IEEE is the IEEE 802.15.4a standard from 2007. This is also the one adopted by Decawave and currently the most commonly used. It also defines both the physical and medium access control aimed towards applications with short-range and relatively low data rates from a UWB perspective.

The current state of the IEEE 802.15.4a standard specifies 4 different data rates; 110 Kbps, 850 Kbps, 6.8 Mbps and 27 Mbps divided over 15 different frequency bands. The various channels provide selectivity in terms of allowed spectrum utilization and simplify the compliance of regulations set on this technology which will be discussed in the next section, thus promising at least some channels authorized by regulatory bodies in most of the main
4.5 Implementation Factors

geographies worldwide and thereby available for vehicular applications.

4.5.4 Regulations

One important consideration affecting the UWB protocol is the regulations associated with this technology due to the extensive bandwidth. In order to be compliant with the spectrum regulatory requirements, maximum values must be ensured in terms of power and mitigation techniques. The following figure is an extract from the Swedish Post and Telecoms Agency [56] in association with the regulatory organization Electronic Communication Committee (ECC).

![Figure 4.9: Maximum value of mean power spectral density limit (e.i.r.p) from the commission decision 2014/702/EU](image)

A maximum mean power spectral density of -41.3 dBm/MHz (75 nW) are allowed together with a few conditions referred to as notes. Each note refers to limitations in transmission techniques such as low duty cycle (LDC), detect and avoid techniques (DAA), and transmit power control (TPC) where each regulated value has been defined in accordance to the relevant harmonized standard for each technique.

One of the major drawbacks brought from these strict regulations involve the diversity associated with the global regulations put on the spectrum allocation. The only conjunctive factor is the maximum mean equivalent isotropic radiated power (EIRP) level as seen in figure 4.9. The collective agreement

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3Within the band 3.1 GHz to 4.8 GHz and 6 GHz to 8.5 GHz, devices implementing LDC mitigation technique are permitted to operate with a maximum mean e.i.r.p. spectral density of -41.3 dBm/MHz and a maximum peak e.i.r.p. of 0 dBm defined in 50 MHz. Operation is in addition subject to the implementation of an exterior limit of -53.3 dBm/MHz.

4Within the bands 3.1 GHz to 4.8 GHz and 8.5 GHz to 9 GHz, devices implementing DAA mitigation technique are permitted to operate with a maximum mean e.i.r.p. spectral density of -41.3 dBm/MHz and a maximum peak e.i.r.p. of 0 dBm defined in 50 MHz.

5Within the band 6 GHz to 8.5 GHz devices implementing TPC mitigation technique and an exterior limit of -53.3 dBm/MHz are permitted to operate with a maximum mean e.i.r.p. spectral density of -41.3 dBm/MHz and a maximum peak e.i.r.p. of 0 dBm defined in 50 MHz.
of -41.3 dBm/MHz power remain valid globally while the available spectrum on this level varies quite a lot [55].

The allowed spectrum in the U.S was set in 2002 by the Federal Communications Commission (FCC) and remains the most liberal one from the allowed spectrum point of view. The maximum mean EIRP of -41.3 dBm/MHz can be used from 3.1 GHz up to 10.6 GHz which can be seen in figure 4.10 below. This is the only spectrum that grants the use of all different type of UWB techniques and modulations, thus allowing higher freedom in terms of optimization. Krebesz et al. [57] performed a study mathematically optimizing a communicative vehicular application from the current regulations provided by the FCC. The study provided solid ground in terms of recommended approach towards a combined architecture within the vehicle, applicable on all deviating jurisdictions.

The Chinese UWB spectrum was set in 2008 by the Ministry of Industry and Information Technology (MIIT). The available spectrum width is however relatively narrow compared to both US and European regulations. There are two different bands allowed for the maximum mean EIRP of -41.3 dBm/MHz transmissions ranging from the lower band of 4.2 – 4.8 GHz to the higher band of 6 – 9 GHz. China has approved the use of UWB for the appropriate ECMA standard and many of the constraints on the use of UWB equipment are in line with other common jurisdictions associated with this technology worldwide.
Figure 4.11: Max. mean emission limits for UWB China [59].

The European UWB spectrum was set in 2006 followed by two updates in 2007 and 2011. The allowed spectrum also features two possible bands with the same maximum mean EIRP limit as the US and Chinese regulations. The bands are between 3.1 – 4.8 GHz and 6 – 8.5 GHz. The lower band of 3.1 – 4.8 GHz can only be used if the transmission has adopted the regulatory techniques described in section 4.1 about the UWB protocol, corresponding to either detect and avoid (DAA) or low duty cycle (LDC). The higher band of 6 - 8.5 GHz demands the use of DAA in order to be used.

Figure 4.12: Max. mean emission limits for UWB European Union [60].

The diverse regulations pose as a challenge for the intra-vehicle implementation by either adopting the used UWB transmission to satisfy all different constraints or by customizing the network towards different jurisdictions globally.

4.6 Summary

The intention of this final section is to present a selection of the most important aspects discussed in the analysis above. The complexity involved when evaluating a wireless channel caused by a multitude of dependencies and convoluted parameters as previously discussed generally contribute to a nontrivial determination of the channel behavior. Therefore, a summary of
the most conclusive factors can be seen below.

The following two pages consist of brief highlights associated with both beneficial aspects and drawbacks associated with both Bluetooth Low-Energy and Ultra Wide-Band technology.
4.6 Summary

Bluetooth Low-Energy

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td><strong>Power consumption</strong> is slightly lower compared to the UWB counterpart, enabling constrained battery operation to last for years without interruption.</td>
<td><strong>High path loss</strong> reaching levels over 80 dB. Network design must therefore consider critical aspects such as spatial placement, target compartment, and sufficient transmission power.</td>
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<tr>
<td><strong>Simplifying assumptions</strong> such as the WSSUS model can be utilized when designing the network and overall channel behavior will be easier to determine due to the narrowband frequency characteristics.</td>
<td><strong>Physical layer security</strong> where vulnerability to jamming attacks may compromise the entire transmission, regardless of higher layer security measures.</td>
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<tr>
<td><strong>Flat-fading</strong> channel performance simplifies the network design in a way where fading will be correlated over the entire bandwidth, thus enabling simplified design and higher possible transmission rates.</td>
<td><strong>Interference</strong> when exposed to similar external technologies in close proximity. The widely used 2.4 GHz frequency spectrum together with the narrow bandwidth causes interference to and from external devices utilizing the same band, establishing an unpredictable and highly dependent source of interference.</td>
</tr>
<tr>
<td><strong>Higher layer security</strong> protocols has been developed and optimized during the long run as a popular wireless technology. A wide selection of efficient security measures can be found customized to the specific need.</td>
<td><strong>Low transmission rate</strong> relative to the UWB counterpart. Even though 2 Mbps in many ways might prove sufficient, especially when compared to the current CAN technology, there is just no match to the achievable rates associated with UWB. Limitations therefore exist in terms of more sophisticated systems such as Advanced Driver Assistance Systems (ADAS) and demanding multimedia applications.</td>
</tr>
<tr>
<td><strong>Maturity</strong> obtained through the widespread use and attention has provided a plethora of diagnostic tools, selection, and overall understanding of this protocol. The impacts include lower prices, wider selection and plenty of references to rely on in the event of an implementation.</td>
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Table 4.1: A brief summary of the beneficial aspects of BLE weighted against the drawbacks, all applied towards the intra-vehicle application.
Ultra Wide-Band

**Pros**

- **Low path loss** in comparison with Bluetooth technology where power losses ranging between 30 - 40 dB rather than > 80 dB in the BLE case.
- **Cooperation** and **co-existence** with other wireless technologies was found true also in the intra-vehicle domain. Thus removing the risk of unpredictable events where external wireless devices and geographic locations containing wireless access (Wifi etc.) might cause interference and impact network performance.
- **Security trade-off** has been found in emerging technologies where parts of the extensive bandwidth can be used for security and reliability measures instead of enhanced transmission rate.
- **High transmission rate** enabled by the wide bandwidth establish potential rates above the Gbps rate.
- **Low power consumption** compared to other wireless technologies, even though BLE is slightly better.
- **Multipath resistance** proven to be a reliability in the intra-vehicle implementation where harsh conditions caused by dense scattering and metallic surroundings is mitigated by the robustness and tolerance provided by the wide bandwidth.

**Cons**

- **Frequency selectivity** contribute to complexity and dependency of the overall channel behavior. Type of modulation will contribute to significantly different result and deterministic models are no longer as reliable and simplistic as the narrowband counterpart.
- **Selection** of devices and solutions is still scarce due to the periods of passivity caused by competition from other wireless technologies. Recent years has seen a lot of momentum and emerging solutions for UWB fortunately.
- **Higher layer contributions** is significantly less available compared to the Bluetooth counterpart. Where the Bluetooth protocol offer a wide selection of available solutions and comprise of several layers, UWB simply focus on the two lower layers. This doesn’t necessarily need to be a drawback however where a freedom of customization and choice can be established in terms of security, software design and transmission properties.
- **Simplifying assumptions** such as the WSSUS assumption cannot be utilized due to the frequency dependent behavior caused by the wide bandwidth, thus complicating the overall channel behavior associated with UWB.

*Table 4.2:* A brief summary of the beneficial aspects of UWB weighted against the drawbacks, all applied towards the intra-vehicle application
The evaluation also reported a few critical aspects targeting the general channel model associated with the intra-vehicle characterization. Neglecting the contrasting behavior caused by the opposing properties of each wireless protocol, here are some of the most crucial aspects reported.

- **Slow-fading** behavior derived from the coherence bandwidth can be regarded as a immensely fortunate property where transmission rates, design complexity and thereby overall costs will benefit from this channel tendency. Symbols and even entire frames can be transmitted without significant difficulty since the channel will remain stationary.

- **High path loss** can still be considered a defining aspect caused by the intra-vehicle environment. Considerations is necessary when including several compartments, or general *Non-Line-of-Sight* (NLOS) deployment which is highly expected in the vehicular application.

- **Strong multipath** tendency and dense scattering is one of the most governing aspects associated with the intra-vehicle environment. Realized by the internal anatomy and materialistic properties associated with the vehicle, Rice distribution was reported when Rayleigh distributions theoretically would have been a better fit. The lack of a dominant component associated with Rayleigh is compensated by a rich multipath propagation where a superimposed signal results in Rice behavior. Multipath fading inside the vehicle may also degrade the signal strength at the receivers, impacting on their ability to decode the received signals. These factors give rise to the hostile nature of the wireless channel and must therefore be considered.

- **Time-invariant** is another fundamental and beneficial aspect where complexity obtained from Doppler effects and frequency distortion causes insignificant contributions. The effect is a relatively simplistic channel model where time consuming and costly considerations required in a highly time-variant channel can be neglected. This further implies that sensor mobility and routing configuration is less of a problem.

As stated in the aforementioned chapter, the intra-vehicle environment offer a combination of some of the most devastating aspects of wireless design such as high path loss and dense operation together with beneficial and highly appreciated tendencies like time-invariant behavior and slow fading. It is therefore critical when making design considerations to mitigate demonstrated threats and exploit proven beneficial factors in order to provide a promising network potential. The time-invariant nature and slow fading for example can be utilized by allowing higher transmission rate without the need of advanced receivers while the high path loss and multipath tendency can be
mitigate through intelligent spatial considerations in each individual link. This topic will be the case in the next chapter where design considerations based on previous evaluation will be presented together with constraining limitations and challenges.
Conclusion

The previous chapter provided a general picture of the intra-vehicle environment and the resulting impact it has on the wireless propagation. It further provided a more specific description on the individual performance viewed from BLE and UWB point of reference. When designing a wireless network, it is vital to understand the radio propagation characteristics in the target application. The feasibility of various technologies highly depends on whether enhancements can be made by utilizing promising behavior while mitigating the effects of potential drawbacks such as interference and fading. Thorough knowledge of the channel is therefore critical in order to select the most prominent protocol, thus optimizing overall network performance while reducing relevant factors such as power consumption and overall implementation costs. In this chapter we review the highlights from previous chapters and conclude the most prominent potential and challenges for the intra-vehicle channel.

5.1 Limitations

The most prominent limitation associated with UWB is related to the strict and diverse regulations put on the spectrum allocation. As described in section 4.5.4, different jurisdictions maintain contrasting limits on the allowed spectrum together with obligatory mitigation techniques in some areas. Since vehicles all relate to a global market, an implemented UWB network must either satisfy all different constraints or customize the network towards different jurisdictions globally. The only common frequency band that can be used for transmission within the limitations set by all the three regulatory bodies is 3.4 – 4.8 GHz and to 6 – 8.5 GHz if the DAA or LDC is applied. Utilizing the OFDM-UWB modulation technique is one possible way to bypass these regulations and adapt to the global restrictions.

BLE on the other hand face the possibility of limitations in terms of obtainable transmission rate. The current established 2 Mbps might in some applications prove too low, especially when considering trade-off in security and cryptography. When implementing new networks, it is critical to design long term solutions and regard sustainable development such as emerging trends potentially associated with the current adaptation. The recent expansion of sensors and sophistication within vehicular domain might very well pose as a threat in the near future and force BLE to make room for
a more capable technology in terms of transmission rates. It is therefore important to evaluate the target application within the vehicle and reason whether future trends on the specific target face the risk of demanding higher transmission rates.

5.2 Requirements

The implementation of a wireless sensor system within a vehicle involves a number of unique characteristics, and specifies certain design requirements in order to achieve sustainable performance.

*Low cost* can be considered one of the most vital aspects in order to motivate the transition towards wireless transmission. The current wired architecture regard this particular aspect one of the biggest advantage since both LIN and CAN architectures are relatively cheap solutions. Lower complexity generally implies lower cost, so if the system can adopt existing wireless solutions with minimum modifications, or integrate the wireless architecture with the wired through compatible higher layer protocols and various compatible solutions, then the complexity of the transition and thereby the overall cost will be decreased.

*Short delay* are desirable for some of the potential applications. Non-critical, real-time systems together with human interactive systems require prompt response. Failing to do so might compromise the real-time functionality or cause general user discontent. In the vehicular domain, this particular aspect therefore counts as a critical requirement with varying necessity depending on the application.

*Security* and *reliability* is additional crucial aspects since wireless extensions to the internal vehicular network will have performance degradation in terms of reliability compared to the wired network. Depending on the application, different levels of security measures will be needed and the resulting degradation will depend on the trade-off between security and bandwidth. Achieving high communication reliability is possible with both protocols but will affect other desirable properties such as delay, transmission rate, or power efficiency. Note also that wireless channels cannot compete with wired solutions in terms of reliability in the current state. Vital systems that require low latency and high reliability to satisfy the stringent requirement of real-time intra-vehicle control such as the power train and engine control won’t be the target for wireless adaptation. UWB possess greater options in terms of security trade-off since the wide bandwidth and achievable transmission rates can be interchanged with various security measures while still maintaining proficient performance. BLE on the other hand has a higher impact
on the relative performance when trading transmission rate and bandwidth to physical security.

Cooperation with both currently existing and potentially appearing systems is another key requirement when integrating new systems. Mutual cooperation and co-existence is therefore crucial where current internal systems as well as external commercial products brought within proximity cannot interfere significantly with each other. BLE runs the risk of both interfering and being interfered with other narrowband systems such as general Bluetooth devices, Wi-fi and other common wireless products operating in the ISM spectrum.

5.3 Potential

This section briefly discusses some of the beneficial aspects extracted from the intra-vehicle analysis and how certain design considerations has the potential to enhance performance.

Continuing the elaboration regarding low cost, a multitude of factors must be considered in order to obtain a realistic estimate of potential cost. As described in section 4.4.3, even then the amount of variables involved might change the actual outcome from an economical perspective. BLE currently has the advantage in terms of market adoption, widespread knowledge and diagnostic tools, as well as both selection and price for each individual device. All these factors influence the overall integration prices of BLE in the vehicular domain which in turn result in a significant motivation to choose this technology as the target platform. UWB on the other hand, with a history of struggle on the wireless market, has the potential to act more like an investment. With the sustainable attributes such as wide spectrum interchangeable with security, transmission rate and overall performance, the UWB technology stand a higher chance to cope with future growing sophistication and performance demands.

Additionally, since UWB only define the two underlying layers in the protocol stack, the remaining layers can be shared among the rest of the wired architecture. Thereby sharing a common approach throughout the entire vehicular network regardless of physical media protocol. In this way many other industry protocols can reside on top of the UWB platform such as Ethernet and High-Definition Multimedia Interface (HDMI). Ethernet has recently emerged as a wired architectural approach throughout the car industry due to its low cost, transmission rate, and flexibility [61]. Operating within the same physical layers as the UWB protocol, the same stack can be adopted throughout the entire vehicle, including the security approach. While still capable of adapting other protocol layers, the BLE protocol is
defined as an individual stack where security and other software approaches is distributed and optimized throughout its own individual stack design, thereby making it more complex to integrate with the Ethernet exclusive stack. As a result, both sustainability through future spectral trade-off and friendly integration with existing wired technology has the potential to decrease overall implementation costs of the UWB technology in the vehicular domain.

Instead, BLE has considerable benefits to bring from the widely adopted market. The integration with cell phone technology and commercial products enables several possibilities where electronic welcome and interactive multimedia platforms can be established. For example, due to the personal use of cell phones in combination with the individual identification associated with each device, driver settings such as seat, mirrors, steering wheel, and even vehicular software settings such as internal climate and multimedia can be customized to each individual driver before entering the vehicle. By sensing the BLE signal and more specifically a unique wireless identification, all settings can be adjusted before the driver reaches the vehicle. This is referred to as electronic welcome and can relatively easy be established with the help of BLE and the associated adoption in the cellular market. Note however that, due to security reasons, applications like these would be based on individual and independent systems in order to remove the risk of compromising the internal network. Nevertheless, utilizing a Bluetooth gateway or similar solutions, electronic welcomes could be a standard application for modern vehicles. In this way, multimedia applications such as games, video and music can be designed where cell phones and commercial products are relatively easy brought into the equation by integrating control or user preferences from both driver and passengers.

Once a comprehensive understanding of the wireless channel has been established, there are several efficient techniques that can be used either independently or in combination in order to combat the interference and fading caused by the harsh vehicular environment. Since the time dependent parameters tend to vary relatively slowly in this channel as realized by the large coherence time in the previous chapter, mitigating techniques such as antenna diversity, equalization, channel coding, modulation schemes, adaptive power control, automatic-repeat-request (ARQ) schemes, etc. can be taken into consideration in order to make intelligent design choices on issues associated with the channel.

Antenna orientation has repeatedly been noticed to play a significant role in the overall channel performance [34]. Due to the emplacement and dense contrasting surroundings, the radiation pattern of the multipath components will cause dissimilar polarization characteristics on various spatial locations.
5.4 Challenges

In combination with the stationary deployment of sensors and antennas, performance optimization can be reached by investigating individual links and customizing the angular orientation towards the most crucial transmission path.

Another beneficial aspect, which also highly depends on the future direction of development, includes the natural attenuation of electromagnetic waves associated with the metallic vehicular chassis. As previously stated, metallic objects have a long history of aggravating wireless network design due to the high path loss (or even blocking) of wireless signals. Since the sensory system associated with the vehicle involve an internal deployment, where exceptions can be made by uniting external antennas and interconnections, the natural attenuation can be utilized by preserving the propagating energy within the vehicle while blocking any kind of external threats and interference. In this way, the entire vehicle will be able to replicate a Faraday cage\(^6\) where any kind of external electromagnetic interference will be blocked. The reason why future direction of development is such a dependency is because of the resulting complications. In order to achieve a significant energy preserving effect, polarization is fundamental on the glass windows. This will however prevent all types of wireless signals from entering the vehicle, including telecommunication and mobile networks. By integrating the vehicle with individual access-points that provide both Internet and telecommunication functionality, both preserved energy enhancing the internal network as well as prevention against cell phone usage while driving can be assured by forcing a more conditional usage.

5.4 Challenges

The intra-vehicle deployment faces a few serious challenges that need dedicated considerations in order to mitigate potential threats. This section aim to acknowledge some of these challenges and discuss potential risks.

The metallic surroundings have been a recurrent topic in this thesis, mainly because of its prominent role in the intra-vehicle deployment. The natural attenuation caused by this material act as both a major design challenge as well as potential advantage as discussed in the previous section. It is vital to regard this attenuation when considering aspects such as protocols, spatial positions of sensors, and radio traffic. General indoor models no longer function as accurate approximations due to the metallic surroundings and unique physical environment associated with the vehicle.

\(^6\)A Faraday cage is an enclosure based of conductive material that block any kind of electromagnetic fields from passing through, named after the renowned scientist Michael Faraday \([62]\).
Even though current attention towards vehicular networks has brought a lot of insight in the channel model, there is currently a lack of unified models that can be applied for all different traffic scenarios. Whether the model is based on dense urban traffic, highway scenarios, or sparse country roads, the channel might behave differently. It is therefore critical to evaluate the internal channel behavior based on contrasting scenarios in order to provide a comprehensive picture of the overall behavior. Extensive channel sounding campaigns and general evaluation built upon highly contrasting environments would be beneficial for future development. Any kind of deviating results and performance must be taken into consideration in order to optimize the wireless system and mitigate deficiencies.

Continuing the trace of deviating result and acknowledging the unpredictable nature associated with the commercial vehicle, considerations must also be given within the chassis. In the same way that the car is designed to travel long distances, thus potentially visiting highly contrasting environments and external scenarios, the car is also designed as an unrestricted asset where personal belongings and devices should be functional unhindered. Passengers within the vehicle should be able to use wireless headphones, computers, cell phones and similar commercial wireless products without interference or impacting the internal system performance. The unpredictable nature of both external and internal aspects will remain a critical challenge where safety precautions must be made.

Security is another recurring topic due to the fundamental impact it has on the vehicular application. Many types of challenges can be traced to this topic where reliable and robust transmission is critical for potential deployment. Making intelligent and preventive design considerations such as efficient cryptographic algorithms, robust hardware and software protocols, as well as strategic deployment of the network beneath the chassis, exposure to attackers can be aggravated without influencing the overall capacity and performance of the network.

As final words in this concluding chapter, the advances of wireless communication within the vehicular domain have the potential to help reshape the future of personal transportation. Inter-connected vehicles with sophisticated internal networks will no longer be information-isolated clusters independently enhancing their individual performance. By means of intra-vehicle communications and inter-connected vehicles, information generated by complex control systems, on-board sensors, or passengers can be effectively distributed among vehicles, pedestrians and infrastructure in close proximity. A variety of active safety applications and advanced driver-assistance systems such as collision detection, lane changing warning, and cooperative merging can be shared in order to establish sophisticated swarm intelligence.
An enhanced social and interactive environment can further be established within the internal network where infotainment applications such as interactive gaming, network sharing and demanding multimedia applications can be available for passengers and co-pilots alike.
Future Work

The following brief chapter is intended to encourage future development associated with the subject of this thesis and hopefully motivate readers with research opportunities of intra-vehicle connectivity.

As previously stated, enhancement and optimization of the communicative aspects surrounding vehicles offer great potential in future development. Several topics included in this thesis have only been briefly mentioned and would therefore require justification in order to provide a better approximation of their dependency. The following aspects are just a few of the potential future research topics available.

Security associated with vehicles remains a vital aspect in the car industry, especially since new demands in the architectural approach followed by increased internal sophistication require replacement of current systems. New protocols, whether they are wired or wireless involve certain risks and thereby extensive analyses in order to mitigate potential threats.

Channel sounding and propagating wireless behavior also remain a vital aspect due to its complexity. The research done in this thesis has been based on different scenarios with highly contrasting conditions. In order to optimize network design towards a specific model or environment, comprehensive measuring campaigns and channel sounding would be required specifically aimed towards that certain application.

The car industry further enables a wide spectrum of economical approaches of this particular subject. Market shares, optimized device costs, or more extensive analyses of the economical factors involved during implementation are just a few of many potential research topics involved in this thesis.

In other words, the combination of vehicles, optimized communication, and sophisticated internal systems offer a plethora of available future development regarding the promising subject of intra-vehicle connectivity.
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