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Industrial Electrical Engineering and Automation

Microwave Radar Implementation in Outdoor Home Alarm Systems

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Abstract

The use of short range microwave radars for motion sensing purposes are on the rise in multiple industries, as they are accurate, small in size and relatively cheap. The automotive industry, in particular, has pushed the development forward. Lately, the home alarm industry has also been glancing at the technology. Radars are well suited for outdoor applications as they are insensitive to precipitation, fog and hot weather that has an impact on the performance of the more common sensors used for intrusion detection: cameras and passive infrared (PIR) sensors.

This report investigates how a microwave radar can be implemented as a motion sensing detector in a battery powered outdoor alarm device. Two microwave radars were evaluated before one was chosen for further testing. The experiments were conducted with a focus on the performance of the radar compared to the PIR, as well as the radar's adequacy in an outdoor environment.

The final result is a prototype containing a PIR sensor and a camera together with a 24 GHz radar as a secondary sensor. Even though the radar outperforms the PIR, it is too power consuming to be implemented as the primary sensor of a battery powered device. The report concludes that low cost, low power radar sensor may very well be a part of the next generation home alarms.

Acknowledgements

First and foremost, we would like to thank the R&D hardware team at Verisure for all the help and support we have received, and for entertaining us during coffee breaks and lunches. A special thanks to Olof Blomé for your invaluable knowledge on RF matters and to Robert Johansson for the expert advice you shared with us regarding PIR technology and Verisure products.

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Finally, we would like to thank our supervisors Alexander Israelsson at Verisure and Gunnar Lindstedt at Lund University for continuous support and guidance.

Contents

Acronyms

CW	Continuous Wave.
DSP	Digital Signal Processor.
EM	Electromagnetic.
FFT	Fast Fourier Transform.
FM	Frequency Modulation.
FMCW	Frequency Modulated Continuous Wave.
FoV	Field of View.
GUI	Graphical User Interface.
I	In-Phase.
PIR	Passive Infrared.
Q	Quadrature.
RF	Radiofrequency.

Nomenclature

α	Angle
λ	Wavelength
σ	Radar Cross Section
θ	Phase
A	Amplitude
c	Speed of Light
f	Frequency
f_d	Doppler Frequency
f_{Tx}	Transmitted Frequency
G	Antenna Gain
I	Current
P_r	Received Power
P_t	Transmitted Power
Q	Capacity
R	Range
$R_{discharge}$	Discharge Rate
t	Time
T_0	Period
v	Velocity

Enter, stranger, but take heed
Of what awaits the sin of greed,
For those who take, but do not earn,
Must pay most dearly in their turn.
So if you seek beneath our floors
A treasure that was never yours,
Thief, you have been warned, beware
Of finding more than treasure there.

- J.K. Rowling

1. Introduction

The introduction presents the aims and objectives of this report. Furthermore, the project will be put in a wider context and its significance and importance in the industry explained.

1.1 Background

Ever since the beginning of mankind, there has always been a need to protect what is yours. The list ranges from homes and territories to goods and food. The methods have evolved, but the need is still present.

Today, most of our valuable possessions are kept in and around our homes, that can range in size from the smallest apartment to the grandest of castles. Common ways of protection include the use of locks, cameras and sensors. Generally, cameras and sensors are mounted inside the house, to detect and alert home owners and authorities of ongoing burglary. Though this is important and highly useful, one could argue that measures are taken too late. A successfully interrupted break-in can still cause property damage, such broken doors or windows, as well as consume time from police and other societal resources. Preventing a crime before it occurs is, of course, desirable.

1.1.1 Verisure and Existing Products

Verisure is an international company specialised in home alarm systems. With a wide range of products and services, their connected alarm system is the most common home alarm system in Europe [1]. Verisure develops wireless battery powered products for easy installation and quick incorporation of additional sensors.

One of Verisure's most popular products is the combined motion detection and camera module for indoor use: the Cam-PIR3.5 (figure 1.1). Passive infrared (PIR) sensors detect any motion within its field of view (FoV) and camera images verify the trigger cause.

Figure 1.1: *Cam-PIR3.5, a motion detection and camera module. Figure from [2].*

A common issue with PIR sensors is false alarms caused by anything from sunlight through the window to the family pet. In an outdoor environment, the potential false triggers are greater in numbers. Rain, snow or fog may impact the performance negatively. High summer temperatures may also prevent accurate detection of humans. Because of these issues, this sensor is mainly targeted for indoor use. To increase performance of the motion detection device in an outdoor environment, other sensors that could replace or complement the PIR are investigated. The solution may very well be the old, but tried and tested, radar technology.

1.1.2 Microwave Radar Technology

In recent years, the development of automotive radar solutions has pushed technology forward within the short-range radar field. The applications of radar include adaptive cruise control and emergency brake assistance, among others. As a result of this, radar sensors in and around the 77GHz frequency band (and the previously used 24GHz band) commonly used in cars have become cheaper and more available for other industrial purposes [3].

Because of this advancement in microwave radar technology, Verisure is keen to investigate the use of a microwave radar in an outdoor sensor device to detect intruders before they break in and any damage is done.

1.2 Objectives

The objective of this project is to test and evaluate a microwave radar sensor and its performance as a motion detection device in an outdoor environment.

This includes the primary goals:

- Completing a list of hardware and performance target specifications for a radar sensor in an outdoor environment.
- Selecting two radar sensors. The choice is based on Verisure's preferences and the specification list.
- Comparing the two radar sensors, and choosing one to further evaluate.

- Conducting tests and experiments with the chosen radar according to the specification list.

Depending on the time consumption of the primary goals, it may be possible to develop a prototype. In that case, the secondary objective is carried out:

- Fully integrating the radar sensor and its functionality into a radar and CamPIR3.5 module.

1.2.1 Delimitation and Assumptions

- Only radar development kits are considered, meaning only kits including a radar sensor chip and a microcontroller circuit board (also called baseboard, carrier card or breakout board, referred to as baseboard in this report from now on) allowing for programmable software are of interest. This is to allow for creation of simple test programs and to minimise the time required to get the sensor up and running.
- No more than two development kits are compared in order to permit a more detailed evaluation of them both.
- Only one radar development kit is tested due to time limitations.
- No detailed analysis of the radar signal processing is conducted. The focus of this project is rather the radar hardware and its functionality in an outdoor environment.
- The main focus is the radar sensor and not the baseboard, as Verisure most likely will develop its own baseboard with the desired specifications.
- The typical home is assumed to be a house with a surrounding garden. The technology will be tested and evaluated with this arrangement in mind.

1.3 Method

The first step was to formulate a list of target specifications. The needs are based on legal regulations, hardware limitations, needs and requirement formulated by Verisure. This list includes targets of both a ”need to have” and a ”nice to have” nature.

Secondly, two radar sensors were chosen based on the specification list and input from Verisure. These were then compared and evaluated with the target specification list as a base. This part did not include any physical testing and was only based on data sheet information provided by the manufacturers and a general product research. The most adequate sensor for the purpose of this project was chosen based on the result of a scoring matrix.

In step three, experiments were conducted based on the specification list previously completed. The radar sensor was tested and the results evaluated. An assessment of the performance and the adequacy of the sensor itself and the radar solution was presented.

Finally, the radar sensor was fully integrated into an existing Verisure product and further testing conducted. The process is illustrated in figure 1.2.

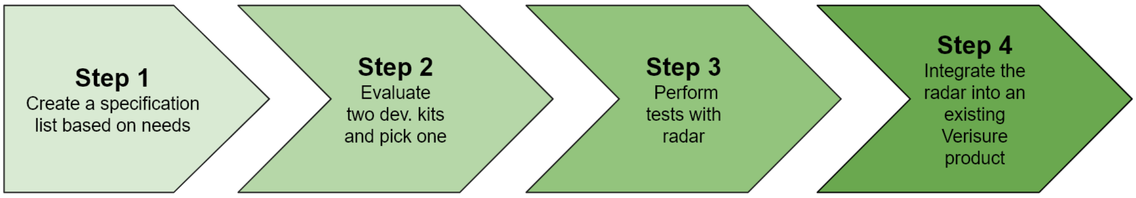


Figure 1.2: *Product evaluation process.*

1.4 Report Structure

Introduction

The introduction contains a background to the topic of choice, including why radar technology is investigated for home alarm purposes and what the aim of the project is. The goals and targets of the report are also presented.

Theory

A review of the theoretical background and knowledge that the project is built upon is presented in the theory chapter. This includes the basics of continuous wave radar technology, the Doppler effect and the properties and essential components of a microwave radar.

Specifications and Choice of Radar

Conclusions of the theory, as well as input from Verisure, result in the specification list. Two radar sensors are compared and one is chosen to go forward with.

Experiments

An explanation and description of the setup for each of the nine experiments with the aim to test the chosen radar is presented. The results of the experiments are visualised in graphs and images and briefly described.

Prototype

A description of the hardware, software and packaging of the prototype are presented in this chapter. The prototype is demonstrated in a performance demonstration to show its functionality.

Discussion

In this chapter, the results and findings of the experiments are discussed. Improvements, issues and future possibilities are highlighted in order to give an overall understanding of the potential of the radar sensor.

Conclusion

The conclusions of the project and the outcome of the discussion are presented together with adequate future work.

1.4.1 Division of Labour

Below is a rough list of the division of labour between the two authors.

Isabelle

Report: Abstract, Introduction (**1.1, 1.2, 1.3, 1.4**), Theory (**2.1**, **2.2**, 2.3.1, 2.3.2, 2.3.3, **2.4**, **2.5**), Specifications and Choice of Radar (**3.1**, **3.2**, **3.4**, 3.5.2), Experiments (**4.1**, 4.2.1, 4.2.3, 4.2.4, 4.2.5, 4.2.6, 4.2.7, 4.2.8), Prototype, Discussion (**6.1**, **6.2**, **6.3**), Conclusion
Other tasks: Experiment recorder, CAD of prototype, Arduino code for radar sensor in prototype, hardware preparations of PIR and radar for Cam-PIR3.5 integration.

Gustaf

Report: Introduction (**1.3**), Theory (**2.1**, 2.2.4, 2.3.1, 2.3.3, 2.3.4), Specifications and Choice of Radar (**3.3**, 3.5.1), Experiments (4.2.2, 4.2.7, 4.2.8, 4.2.9), Discussion (**6.1**, **6.4**),
Other tasks: Experiment tester, integration of radar in the Cam-PIR3.5.

2. Theory

In this chapter, a short introduction will be presented to give context to the basic principles of radar. Thereafter, the radar system will be treated in more detail to give the reader an understanding of the essential components that make up a radar system, as well as the possibilities and limits of radar technology. Lastly, a short description of passive infrared sensors is presented.

2.1 Radar Introduction and History

Radar, short for radio detection and ranging, is the technology of using radio waves to detect distant objects. The radar transmits electromagnetic (EM) waves in the radiofrequency (RF) spectrum, and any objects in the field of view (FoV) will act as a mirror and reflect waves back to the radar. The reflected waves, and their change in characteristics, reveal information about the target, such as its presence, speed, range and direction of motion.

The transmitted EM waves travel with the speed of light and vary in frequency and intensity depending on the purpose of the radar. Traditionally, radar frequencies range between 300 MHz and 35 GHz, though there are applications that require from 3 MHz up to 300 GHz. Microwave radars utilise some of the higher frequencies of that spectrum, from 300 MHz to 300 GHz. This corresponds to wavelengths of 1 mm to 1 m that are suitable for short-range applications.

Historically, radar has been used in long-range military applications and was an important instrument during World War II. Today, radars are implemented in several civilian applications, both long and short range. The technology is employed in air traffic control, marine traffic, adaptive cruise control in cars and for monitoring respiration and heartbeat in the healthcare industry [4].

2.1.1 The Radar Range Equation

The radar range equation in equation 2.1 describes the relationship between the range, R, and the transmitted power P_t, the antenna gain G, the wavelength λ, the radar cross section σ and the received power P_r. They all have an impact on the radar behaviour.

$$R = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{P_r (4\pi)^3}} \tag{2.1}$$

The equation highlights the impact of range: if the range to the target is doubled, the received power is decreased by a factor 16. Thus, the range at which a radar can operate is determined by the sensitivity of the receiver as described in equation 2.2 [4]:

$$R_{max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{P_{r_{min}} (4\pi)^3}} \tag{2.2}$$

2.2 Radar Properties

As radar sensors have many applications, the properties of the sensors vary with range and purpose.

2.2.1 The Doppler Effect

When a source of EM waves moves in relation to an observer, the registered frequency is different from the transmitted one, and this shift in frequency depends on the relative speed between the two. The same relation applies for sound waves, and most people have experienced this when the pitch of an emergency vehicle's siren varies as the vehicle is passing by in high speed. This phenomenon is called the Doppler effect [5].

A radar transmits EM waves at a known frequency. When the waves hit a target, the Doppler effect causes the frequency to shift. The difference in frequency between the transmitted and the received wave can be used to determine the target's direction of movement and velocity. This is depicted in figure 2.1.

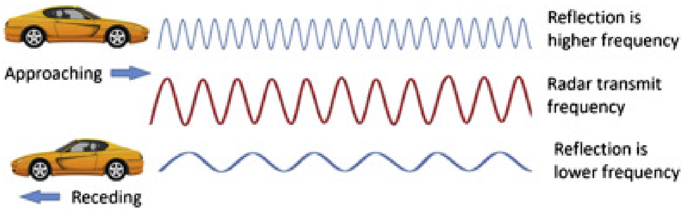


Figure 2.1: *The Doppler effect causes the returned EM wave frequency to be either higher or lower depending on the target's direction of travel. Figure from [6].*

The Doppler frequency, i.e. the difference between the transmitted wave, f_{Tx}, and the frequency of the received wave, is commonly denoted by f_d. The equations below show the relation between the velocity of the target and the Doppler shift:

$$
\begin{aligned}
f_d &= \frac{2f_{Tx}v}{c}cos\alpha \\
v &= \frac{cf_d}{2f_{Tx}cos\alpha}
\end{aligned}
\tag{2.3}
$$

where α is the angle between the target's direction and the beam centre and c is the speed of light [7]. Assuming the radar receiver is stationary and that $f_d = f_{Tx} - f_{Rx}$, an object approaching the radar makes f_d positive (v positive) and when an object is moving away from the radar, f_d is negative and thus is v also negative. The assumption that an approaching target has a positive velocity and a receding a negative velocity will be applied throughout this report.

2.2.2 Waveform

The two main radar waveforms are the continuous wave and the pulsed wave, see figure 2.2.

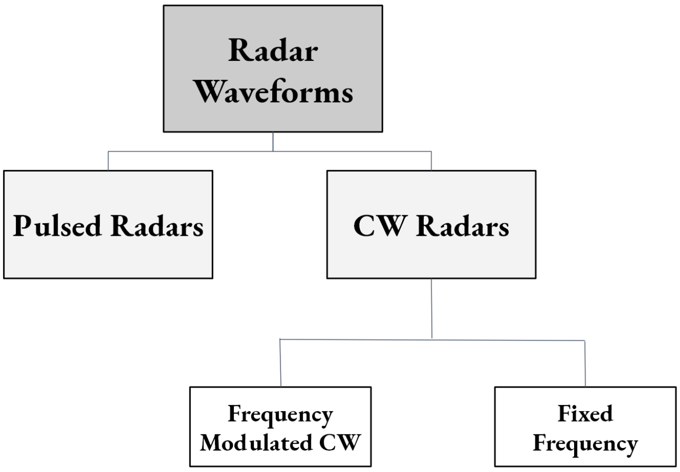


Figure 2.2: *Waveforms employed in radar systems.*

In a pulsed wave radar, the transmitter is turned on for a short period of time to transmit a pulse and is then turned off. The pulse width is usually in the microsecond range, but can vary from nanoseconds to milliseconds. While the transmitter is off, the receiver is on to detect any signal reflections. During transmission, the receiver is blanked (isolated) to protect its sensitive components from the transmitter's high power beam. Pulsing radars are more common in long-range applications as the range allow for longer round times for the pulses. The pulses are transmitted with a high energy allowing them to travel further.

As the name suggests, the CW waveform is continuously transmitted from the antenna, without interruption. Simultaneously, the receiver is listening. CW radars are a lot cheaper to manufacture than pulsed radars. They are generally smaller in size and operate reliably, with few failures. Yet, CW radar systems are sensitive to leakage between the transmitter and the receiver. As any isolation never fully can prevent leakages, the CW radar transmitter is limited to low power and thus a short range, according to the radar range equation 2.1. This is to avoid the transmitted signal from being detected directly by the receiver and causing all reflections to be blocked, known as self-jamming. High frequencies are common in short-range applications as the waves lose their energy quickly due to a high impact of losses, but contribute to a very good resolution.

Because of the continuous transmission and reception of EM waves in a CW radar, it is not possible to determine the distance to the object by only using one frequency, thus solely relying on the Doppler effect. To solve this problem, a technique called frequency modulation (FM) can be implemented. By regularly changing the transmitted frequency, the change works as a timestamp and the round-trip time for the EM wave is determined, as showed in 2.3. As a result, the target range can be resolved using the simple formula in figure 2.3 [4]. A linearly frequency modulated wave, or chirp, is pictured in figure 2.4. By modulating the frequency, it is also possible to individually detect multiple targets in the FoV. This is not possible with an unmodulated signal [8].

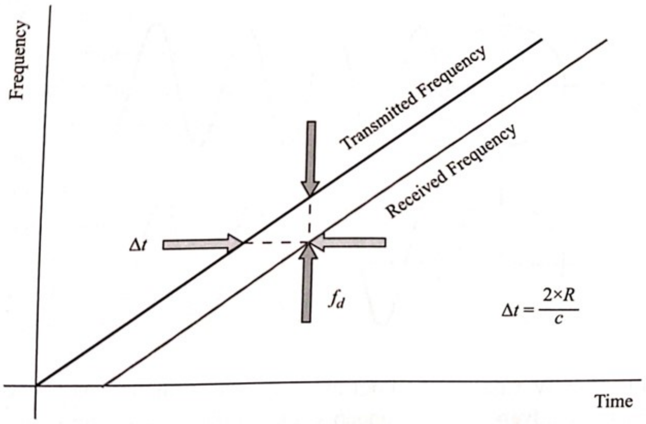


Figure 2.3: *How range is resolved using frequency modulation. Figure from [8].*

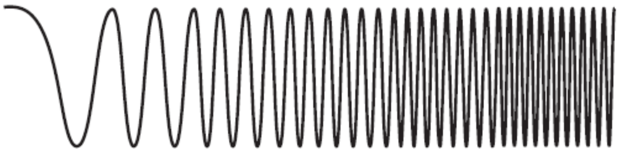


Figure 2.4: *A linearly frequency modulated wave, also known as a chirp. Figure from [4].*

There are also examples of pulsing CW radars today. These are basically CW radars that are turned on for a short period of time before being turned off. Using this technique allows the radar to benefit from the CW waveform, but in a power efficient way. Most of these radars can operate in a pure CW waveform as well [9].

2.2.3 Frequency

The radar operating frequency, f, depend on the wavelength, λ, and the rate of propagation which is equal to the speed of light, c, of the transmitted waves:

$$\lambda = \frac{c}{f} \tag{2.4}$$

The frequency can also be expressed as $f = \frac{1}{T_0}$, where T_0 is the wave period, i.e. the time from any point on the sinusoid to the next corresponding point [5]. Different frequencies and different wavelengths affect the behaviour of the radar. There are several factors to consider that are affected by the frequency and wavelength, such as:

- Target resolution
- Propagation
- Material penetration
- Target properties
- Electromagnetic interference [8]

Target Resolution

For a radar that can distinguish multiple targets in the FoV, the resolution is the ability to distinguish objects in range and in angle. These depend on multiple parameters, such as the beamwidth, which in turn is dependent on the carrier frequency [8].

Propagation

A low frequency wave propagates longer than a higher frequency one, if they are transmitted with the same energy. Radars are generally insensitive to precipitation, fog and other weather conditions. That is why radar is widely used in long range applications, such as air traffic control; however, the impact from weather increases with shorter wavelengths and higher frequencies [4].

Material Penetration

The EM waves in the microwave spectrum will either propagate though a material or be reflected. Most materials are bad conductors of radar waves, with metal being the one exception. This means that EM waves can travel through walls, doors, windows etc.; however, losses increase with material thickness, distance and higher radar frequencies. Below is a graph showing the penetration of radar through different materials [4].

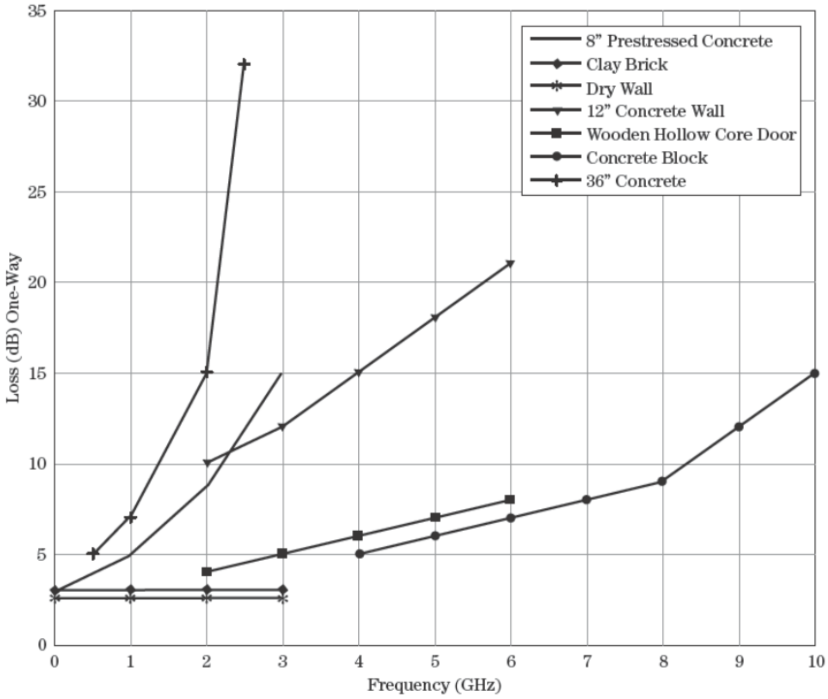


Figure 2.5: *Losses as a function of frequency for radar passing through different materials. Figure from [4].*

Target Properties

The target's characteristics are important factors to consider when choosing an appropriate frequency [8]. One of them is the radar cross-section. While two objects may be similar in size, their electromagnetic signature may be vastly different depending on the shape, the angle of observation and the transmitted wavelength. As shown in figure 2.6, a flat plate and a cone may have the same projection area, but the cone will have a significantly smaller radar cross-section [10].

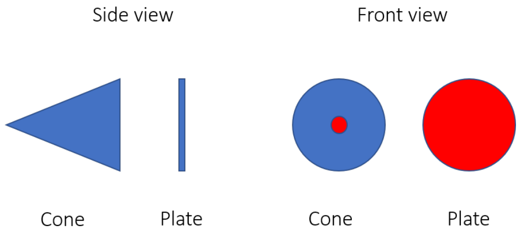


Figure 2.6: *Radar cross-section (in red) of a flat plate and a cone.*

According to the radar range equation 2.1, a larger radar cross section can be detected at a greater range. In table 2.1 below, the radar cross-sections of some common objects are presented.

Table 2.1: The radar cross-section for common targets [11].

Target	**Radar Cross-Section** $[m^2]$
Bird	0.01
Human	1
Cabin Cruiser	10
Automobile	100
Truck	200
Corner Reflector	20379

A corner reflector reflects a signal straight back to the source by having three perpendicular surfaces put together.

Electromagnetic Interference

Electromagnetic interference is disturbing signals transmitted from other devices, that could potentially lead to poor performance or total loss of function. To avoid this, there are rules and regulations that control the use of RF frequencies (more about regulations in section 2.4) [8].

2.2.4 Coherency

A non-coherent system can detect the signal's amplitude but not its phase. All early radar systems were non-coherent. A coherent system, on the other hand, identifies both the amplitude and the phase, treating the signal as a vector. By measuring changes to the phase of a signal, the coherent radar is able to measure sub-wavelength range changes. This ability enables the coherent radar to perform more advance analysis of a detected target. The target can, with a high accuracy, be separated from other targets close by. Its speed and direction of travel is also easily determined [4].

I/Q Detector

To illustrate what coherency means, a double channel detector will be described. In order to do this, a single radar's sinusoidal pulse will be regarded. The pulse is transmitted at the carrier frequency, with the amplitude A and phase θ. The sinusoid can be expressed by the following equation:

$$x(t) = A\cos(2\pi f_0 t + \theta) \tag{2.5}$$

where f_0 is the frequency and the pulse is centred around $t = 0$. The complex amplitude of this sinusoid can be formulated as $Ae^{j\theta}$, if the frequency is known which generally is the case with radar. If this radar pulse, expressed in equation 2.5, is reflected from a target at the range R_0, the time delay from transmission to reception will be $2R_0/c$ seconds. Further, it follows that the received pulse can be expressed as:

$$\begin{aligned} y(t) &= x(t - \frac{2R_0}{c}) \\ &= A'cos[2\pi f_0(t - \frac{2R_0}{c}) + \theta] \\ &= A'cos[2\pi f_0 t - \frac{4\pi R_0}{\lambda} + \theta] \end{aligned} \tag{2.6}$$

where A' is the new amplitude.

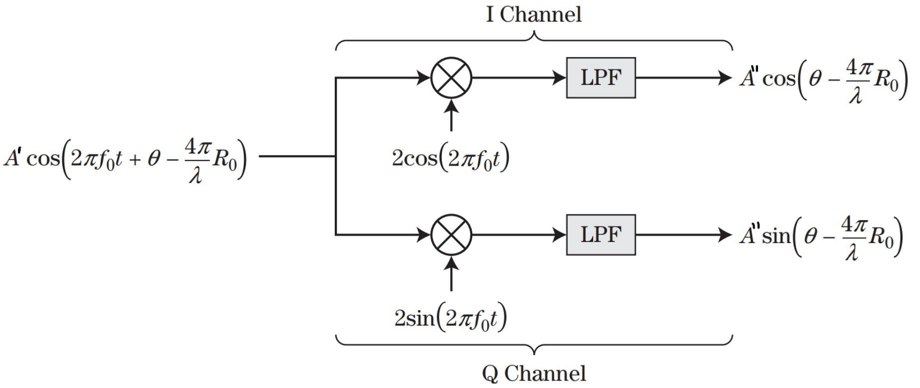


Figure 2.7: *Double channel coherent detector (I/Q detector)[4].*

In a two-channel detector, this received pulse will be mixed with two separate reference oscillators as depicted in figure 2.7. In figure 2.7 there is one channel, the in-phase (I) channel, that uses the same reference oscillator as in a one channel, non-coherent radar. The other channel, the quadrature (Q) channel, uses $sin(2\pi f_0 t)$ as a reference oscillator instead. After the mixer, the signals are put through a low-pass filter which filters out irrelevant frequencies. This set up, with two channels, will provide both the real and the imaginary part of the complex amplitude, thus providing a way to measure both the amplitude and the phase of a signal. The complex signal $y[0]$ can be expressed as:

$$y[0] = y_I[0] + y_Q[0] = A''(cos\theta' + sin\theta') = A''e^{j\theta'} \tag{2.7}$$

where the new phase is $\theta' = \theta - 4\pi R_0/\lambda$. The example above is simplified and the real process in a radar system is more advanced. However, the principle is the same: decomposing the sinusoidal pulse into I and Q components enables the capability to see changes in the magnitude and phase of the wave, and consequently making it easier to interpret the collected signals [4].

Target Speed

As most modern radars are coherent, the target can be identified as moving or not by comparing the phase differences from two or more received signals, as figure 2.8 shows. The phase change is proportional to the radial velocity of the target.

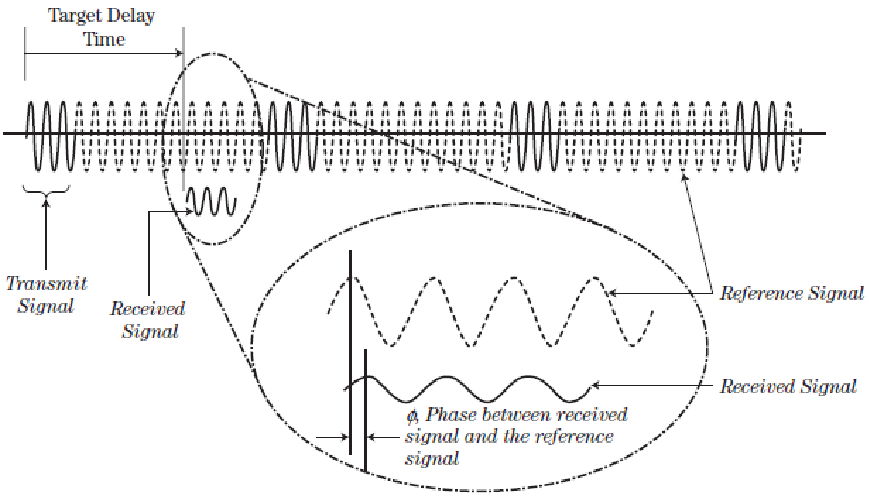
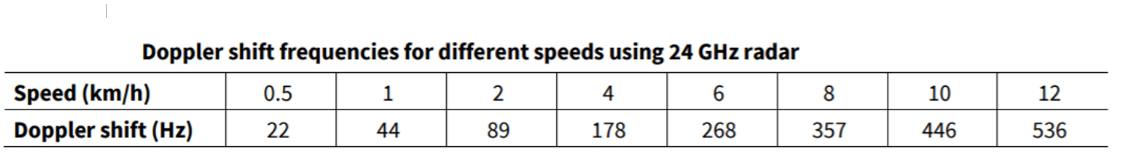


Figure 2.8: *The phase difference between the transmitted and received signal. Figure from [4].*

Determining if the target is moving and, if so, in what direction, is possible after analysis of the frequency shift caused by the Doppler effect (see section 2.2.1). Given the initial signal wavelength and the Doppler frequency, the speed of the target can be determined using equation 2.3 [4].

A radar using a frequency of 24 GHz will generate a Doppler shift of a stationary receiver in relation to a moving target as shown in figure 2.9.



Doppler shift frequencies for different speeds using 24 GHz radar

Speed (km/h)	0.5	1	2	4	6	8	10	12
Doppler shift (Hz)	22	44	89	178	268	357	446	536

Figure 2.9: *The Doppler shift in relation to the target speed of a 24 GHz radar. Figure from [12].*

2.2.5 Bandwidth

The receiver bandwidth determines the span of frequencies that can be detected. When discussing bandwidth, the signal-to-noise ratio is an important factor. The bandwidth is linearly proportional to the noise power, and for that reason, a wider bandwidth is not always preferable. Making the bandwidth very narrow; however, may cause other complications such as a loss of signal strength of the received signal. This also has a negative effect on the range resolution.

The bandwidth also has an impact on how much the signal can be frequency modulated as all frequencies must stay within the frequency band. A narrower bandwidth allows for less modulation, but is favourable from a noise impact perspective. A greater modulation bandwidth allow for a bigger change of frequency over time which in turn will make it easier to resolve the target range and keeps the radiated power spectral density on a low level [8].

2.3 Radar Components

A radar consists of several different components and subsystems. The essential subsystems for radar functionality include the antenna, the transmitter, the receiver and the signal processor [4].

2.3.1 Antenna

The antenna is the radar component that transmits and receives EM waves, though sometimes the transmitter and the receiver are placed on separate antennas. Its purpose is to concentrate the EM waves into a beam that can be pointed in the desired direction. The antenna is the eyes of the radar, implying that only targets in the FoV can be detected.

Figure 2.10 shows the directivity pattern of the beam radiated by the transmitter. This pattern is influenced by the transmission angle. The peak at 0^o in figure 2.10 is where the energy is concentrated and alongside the main beam peak there are side lobes. The angle between the first minimum to the left of the beam peak and the first minimum to the right is called the the beamwidth, or the 3 dB beamwidth [4]. The beamwidth is proportional to the wavelength divided by a the length of the antenna's radiating surface (aperture): $\theta = \lambda / L_a$. This means that at a fixed aperture size, a shorter wavelength, and thus a higher frequency, results in a smaller beamwidth and better angular resolution [8].

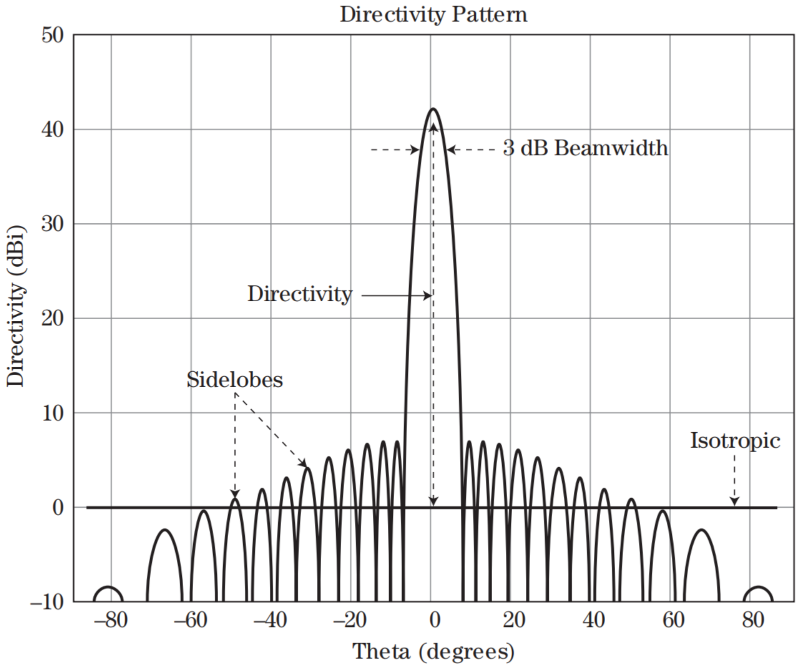


Figure 2.10: *Signal collected by antenna with directivity pattern. Figure from [4].*

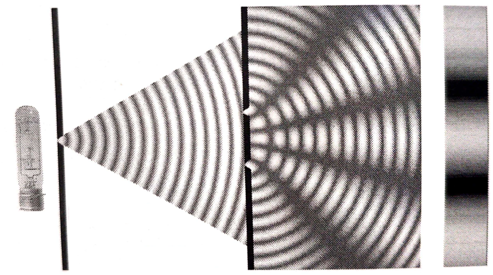


Figure 2.11: *Young's experiment. Figure from [5].*

The effect seen in figure 2.10 is a result of diffraction around the aperture of the antenna and interference between waves. When two or more EM waves interfere with each other, the resultant wave is the complex sum of these waves. This phenomenon was illustrated by the British physicist Thomas Young when he let the light from a monochromatic light source pass through a single slit and then through a double slit, see figure 2.11. If the light passing through is directed at a screen, it will create a pattern of light maximum points and dark fringes [4, 5].

Antenna Arrays

An antenna array is a set of antenna elements that work together as a single antenna. Interference helps to enhance a transmitted signal in the desired direction. The same applies for received signals. The size of an array antenna is largely dependent on the wavelength of the transmitted waves. The spacing between the elements in the array is desired to be as large as possible to increase aperture area and as a result, receive a stronger signal; however, side lobes may cause problems. Side lobes are strong secondary main lobes caused by incoming radiation from other than the main direction that can impair the radar's target location.

In order to avoid this, the elements should be as close together as possible. Commonly, elements are placed half a wavelength apart as this minimises the impact of side lobes as well as maximises the aperture size. This set up is the most adequate one for scanning waves arriving from any arbitrary angle [4].

2.3.2 Transmitter and Receiver Configurations

For CW radars, there are three common configurations of the transmitter and receiver. They are the autodyne, homodyne and heterodyne form.

The autodyne form is often referred to as the simplest form. A block diagram of an autodyne configuration is pictured in figure 2.12. No stationary targets can be detected as only the difference between the transmitted and received frequency, the beat frequency, is measured. For the Doppler effect to occur, the target must be in motion. As this configuration lacks a separate mixer, it is called self-mixing. The mixing, i.e. the extraction and calculation of the beat frequency, is done via the oscillator's non-linearities. The sensitivity of the autodyne configuration is relatively poor as the received signal is competing with the transmitting one, limiting range and velocity estimations.

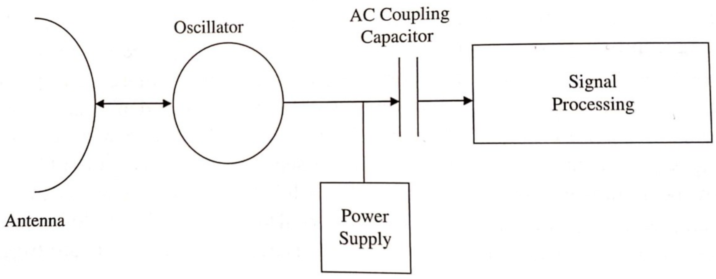


Figure 2.12: Autodyne form. Figure from [8].

The performance of the homodyne form is better than the autodyne due to the use of a separate mixer. Physically separating the transmitter and the receiver improves the isolation between them, as shown in figure 2.13.

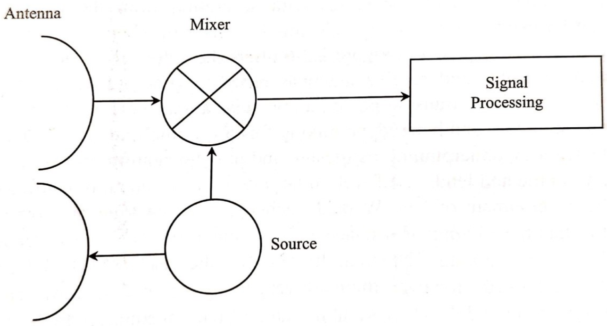


Figure 2.13: Homodyne form. Figure from [8].

The heterodyne configuration offers an even better performance. Instead of mixing the received and transmitted frequencies directly, they are first converted to an intermediate frequency. This helps to separate the received frequency from the transmitted frequency making the difference easier to distinguish. Just as with the homodyne form, separate transmit and receive antennas improve isolation, see figure 2.14 [8].

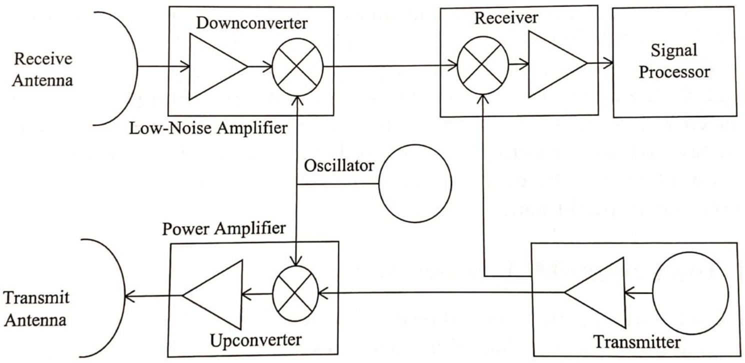


Figure 2.14: Heterodyne form. Figure from [8].

For microwave radars, using an antenna in package (alternatively antenna on package) has become more common, in some applications competing with the traditional separate antennas. Antenna in package means that the antenna is integrated into a chip size package device, often for wireless applications. Antenna in package is more common in high-frequency applications as the short wavelengths allow the antennas to be smaller. This also results in much smaller devices [13].

When transmitting EM waves, it is very important to know what carrier frequency is actually produced, in order to stay within the legally defined frequency bands. There are more than one way to do this, but utilising a phase-locked loop is a common solution. A phase-locked loop is a feedback control system that allows for synchronisation of the transmitted and received signal. A phase-locked loop commonly consists of a phase detector, a filter and a voltage controlled oscillator. The voltage controlled oscillator is essentially an oscillator whose transmitted frequency depend on the input voltage [14].

2.3.3 Signal Processing

To handle the data collected by the receiver of the radar, a signal processor is necessary. The signal processor consists of algorithms that process and analyse the signal input, as well as the hardware on which those algorithms are stored. Since the 1960's, processing has transitioned from previously used analogue methods to modern digital methods. Today, a digital signal processor (DSP) is employed in almost all radar systems as it is superior to the old analogue methods. The biggest advantage with DSP is that it is programmable and thus gives the developer endless opportunities to create different algorithms to handle raw radar data.

The DSP can be viewed as a system with three layers that each has its natural part in the processing of the receiver data. These are shown in figure 2.15. The first layer consists of some initial conditions that the raw data is put through. It comes in the form of filters and/or transformations. An example of a typical filter is a window function, which is implemented to reduce the influence of side lobes.

Further, the most common transform used at this initial stage is the fast Fourier transform (FFT), which converts the data from the time-domain spectrum into the frequency-domain spectrum.

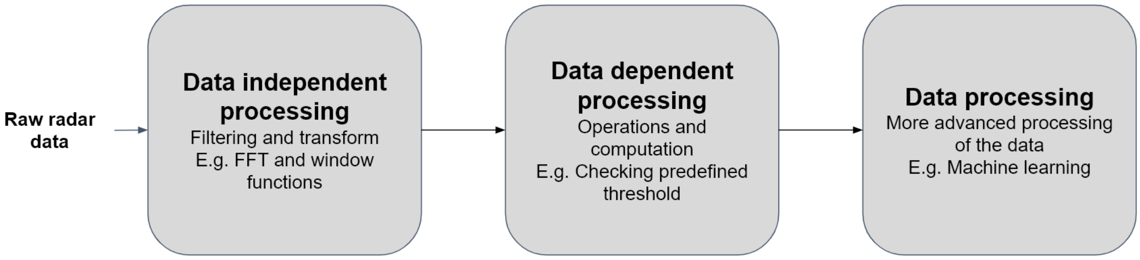


Figure 2.15: *Stages of processing raw radar data.*

When the data has passed through the first layer of the DSP, several operations and computations are done. These operations are dependent on the processed data from the first layer, for example checking if the signal exceeds a predefined threshold. In radar systems, this second layer commonly includes operations such as detection of motion and reading the value of the frequency to determine the velocity of a target.

The final layer consists of more advanced processing and this part is often referred to as data processing. This is where the more complex operations, such as Kalman filtering, take place [4]. Briefly explained, a Kalman filter is used as a tracking filter to make a trajectory of the path the target is moving on [8]. In recent years, machine learning has been implemented at this stage of the DSP and can be used to classify movements of a target.

Today, it is not uncommon to use artificial intelligence to analyse data and determine the type of target. In an article by F. Luo, S. Poslad and E. Bodanese at the Queen Mary University of London, a novel use of machine learning is presented. The algorithm is used for target classification, human activity classification and people counting using data from a simple and low-cost micro-Doppler radar in an outdoor environment [15].

2.3.4 Power supply

By connecting single battery units in series, the voltage is the sum of each unit's voltage and by connecting the batteries in parallel, the current is the sum of each unit's current. When multiple batteries are connected in series and in parallel they are referred to as a battery pack. The capacity, Q, of a battery is in the unit of ampere hours (Ah) and is obtained by multiplying the current, I, by time, t [16].

To estimate the lifespan of a battery pack the following method can be used. By subtracting the total capacity, Q_{total}, with the average current consumption per year, the yearly decrease in capacity, Q, can be calculated according to equation 2.8. This new calculated value of the remaining capacity needs to be multiplied by one minus the average discharge rate, $R_{discharge}$, of the batteries. This leaves the remaining capacity after a year of usage. To obtain the amount of years the pack will last, this method can be used iteratively until the capacity Q becomes negative [17].

$$Q = (Q_{total} - I_{avg} \cdot t) \cdot (1 - R_{discharge}) \tag{2.8}$$

2.4 Rules and Regulations

There are a lot of rules and regulations controlling the use of radiofrequency devices. This is to ensure the health and safety of people, pets and property, as well as to prevent electromagnetic interference and other disturbances.

If a product is to be released on the market in the EU, it must be approved in at least one member state. When it is approved, the product can be distributed in all other EU member states as well [18]. As Sweden is a member of the EU, this section will only go through Swedish regulations and requirements stated by Swedish law and the responsible authority: Post- och Telestyrelsen (The Swedish Post and Telecom Authority).

2.4.1 Frequency Bands

To ensure RF devices do not interfere with one another, there is a frequency plan that states what frequencies can be used for different purposes. Most frequency bands (a span with a lower and an upper limit) require a license from authorities. In Sweden, Post- och Telestyrelsen is responsible for issuing these. Some bands are exempted from this obligation. The bands that do not specify the application or field of use are of great interest for this project as home alarms is not a defined application. The most relevant frequency bands include:

Table 2.2: *Frequency bands [19].*

Frequency Span	Peak Power	Peak Transmitted Power	Peak e.i.r.p. Power Spectral Density
24-24,25 GHz	100 mW e.i.r.p.	-	-
57-64 GHz	100 mW e.i.r.p.	10 dBm	13 dBm/MHz

The acronym e.i.r.p. is short for equivalent isotropically radiated power and is the highest hypothetical power an isotropic antenna can transmit to give the same signal strength as the actual antenna. An isotropic antenna is an ideal antenna that radiates power equally in all directions [19].

2.4.2 Requirements for Distribution

The distributor's obligations are described in PTSFS 2016:5 by Post- och Telestyrelsen. Among other things, the distributor must test and evaluate the device to make sure it works as intended within the right frequency band. A manual and safety information must also be supplied. All distributed RF devices on the European market must be CE marked [20].

2.5 Passive Infrared Sensors

A PIR sensor (figure 2.16) consists of a pyroelectric element that is sensitive to infrared radiation. A change of the infrared radiation causes a rise of temperature in the pyroelectric element. In turn, this causes a change of the electrical properties of the pyroelectric material which results in a measurable change in voltage. The voltage is compared to a threshold level, and if it is exceeded the alarm is triggered [21]. Because a change of radiation is required for a PIR to trigger, the target must be in motion as no stationary objects will be detected [22].

Figure 2.16: *A pyroelectric element. Figure from [21].*

A PIR sensor is, in contrast to a radar, passive, meaning it does not transmit. This feature contributes to a very low power consumption [21].

2.5.1 False Alarms and Undetected Events

Some events may cause a PIR sensor to trigger even though there was no human in the FoV. These are often caused by pets, but also moving rays of sunlight can pose a problem. Weather conditions and animals can impact outdoor sensor performance [22]. The sensitivity to motion can be adjusted, but differentiating a large dog from a crawling human is, according to Verisure, easier said than done.

There are also examples of events that can go unnoticed by the PIR sensor. A few of them are demonstrated in the TV series Mythbusters. By covering the sensor with a glass pane, the tester is able to sneak past without being detected [23] as infrared radiation is obstructed by glass [21]. Another tester managed to mask her infrared signature by holding up a bed sheet in between herself and the sensor and thus passed undetected [23].

There are also reports of poor PIR performance in high temperature environments. As the contrast between a person's radiation and the surrounding environment is what triggers a PIR sensor, it is not possible to distinguish a person if the surrounding temperature is around 32-37^oC, which spans over the surface temperature of the skin [22].

3. Specifications and Choice of Radar

This chapter will state the requirements and specifications of the radar sensor. Also, this part will contain an evaluation of the two competing development kits. After a thorough comparison and a motivation of the decision, the radar sensor of choice will be presented.

3.1 Initial Selection

Before looking at the radar development kits in detail, a short list of critical requirements will be presented. These requirements need to be fulfilled in order for Verisure to consider radar as a viable solution. The list can be seen below in table 3.1. These requirements are based on the performance of the Cam-PIR3.5. Furthermore, the sensor needs to be able to cope with varying weather conditions and outdoor temperatures. As the goal of incorporating a radar sensor is to increase performance, the radar should meet and exceed these demands.

Table 3.1: *Verisure's requirements for the radar sensor.*

	Verisure Required Performance
Range	11.3 m (see figure 3.1)
Field of View	90° horizontally
Speed of Target	0.1-2m/s
Battery Lifetime	3+ years
Legal to use	Yes
Operating temperature	-30 - 70°C

3.1.1 Radar Development Kits

Three radar development kits from Infineon, Acconeer and Texas Instruments, respectively, are provided by Verisure. Verisure has identified these as appropriate for home alarm radar solutions and wants them evaluated. According to the delimitation, only two development kits should be evaluated and thus is one ruled out through a comparison of the critical requirements in table 3.2.

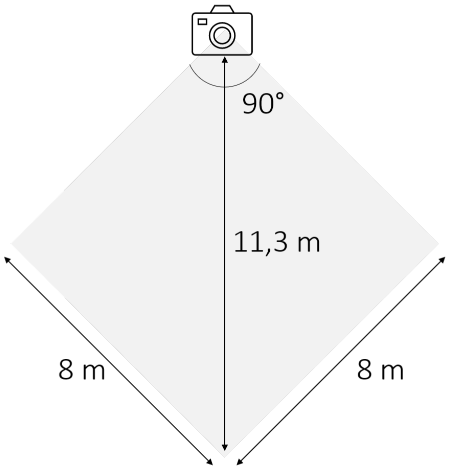


Figure 3.1: *The test area with range and FoV requirements.*

Infineon's Sense2GoL Pulse development kit is a 24 GHz pulsing continuous wave (CW) radar consisting of a microcontroller baseboard and a separate radar front-end board, see figure 3.2. The radar operates within the 24 - 24.25 GHz band, transmitting constant-frequency pulses. Because the frequency is not modulated, range cannot be resolved; however, speed and direction of movement are [12].

The Acconeer XB112 shown in figure 3.3 is a small and compact 60 GHz radar chip with antenna-in-package. It is a pulsed coherent radar, a type of pulsed radar. The sensor is specifically tailored for short-range high-resolution applications, measuring with millimetre precision [24].

The development kit including the mmWaveICBOOST baseboard with antenna plug-in IWR6843ISK provided by Texas Instruments is a 60 GHz pulsing FMCW transceiver with a separate antenna plug-in board, pictured in figure 3.4. The large bandwidth of 4 GHz (60-64 GHz) allow for chirps (frequency modulated waves) to be transmitted, but also make the sensor sensitive to noise as the signal-to-noise ratio is low. The FMCW configuration allows the radar to determine the distance to the target, as well as the speed and direction of movement. The TI radar utilises a phase-locked loop to ensure that the chirps stay within the frequency band [25].

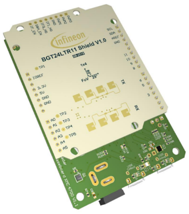


Figure 3.2: *Infineon. Figure from [7].*

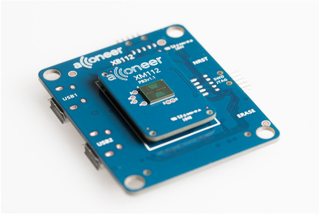


Figure 3.3: *Acconeer. Figure from [26]*

Figure 3.4: *TI. Figure from [27].*

In table 3.2, the critical requirements are stated for the three sensors, respectively. The critical requirement regarding the battery lifetime is not included in the matrix because of the difficulties to determine the power consumption just by studying data sheets. The software settings of the radar sensor can have a great impact on the power consumption.The battery lifetime is also highly dependent on the number of batteries and their type.

Table 3.2: *Critical requirements for the Infineon, Acconeer and TI sensors.*

Criteria	**Infineon Sense2GoL Pulse**	**Acconeer XB112**	**TI mmWaveICBOOST & IWR6843ISK**
Range	20 m	2 m	25 m
Field of View (h)	80^o	70^o	108^o
Speed of Target	up to 3 m/s	-	up to 55 m/s
Legal to Use	Yes	Yes	Yes
Operating Temperature	-40 - 85^oC	-40 - 85^oC	-40 - 105^oC

As Acconeer's XB112 only has a range of two meters and a slightly narrow FoV, it is ruled out. The FoV of Infineon's Sense2GoL Pulse is also a bit narrow, only 80^o [12] while the requirement is 90^o. If this sensor turns out to be the best performing one and the sensor of choice in a Verisure mass-produced product, it is possible to redesign of the antenna to widen the FoV up to 100^o according to Infineon [28].

Thus, the two radar development kits that are chosen for evaluation are the Sense2-GoL Pulse from Infineon and Texas Instruments' mmWaveICBOOST baseboard with antenna plug-in IWR6843ISK.

3.2 Use Case

There are different set-up scenarios for the final product depending on the possibilities and limits of the chosen radars. Below is a presentation of three use cases identified by the authors and Verisure representatives as relevant for this application:

1. Replacing PIR with Radar

Replacing the PIR sensor in a PIR and camera device would require the radar to be active at all times, when the system is armed. The camera would be activated by the radar instead of the PIR. This will likely improve the system performance in terms of false alarms and exclude various flaws of the PIR sensor. This will also increase the power consumption for the system.

2. PIR with Complementing Radar in Sleep State

This option is more effective with regards to power consumption as the PIR sensor consumes power in the range of tenths of mW. In the case that the PIR is triggered, it would wake the radar from its sleep state in order to validate the triggering event. This could prevent false alarms as well as lower the power consumption.

An important factor in this case is the radar boot time from sleep state to the first measurement. This must be rather quick as the target may be moving out of the FoV. Another factor is the radar power consumption in sleep mode that needs to be low enough to retain the battery lifetime on a decent level.

3. PIR with Complementing Radar in Off State

If the radar power consumption is too high in sleep mode, turning off the sensor is another option. This requires that the cold boot time, i.e. the time from power on to first measurement, is short enough for the radar to wake and scan the area for targets.

3.3 List of Specifications

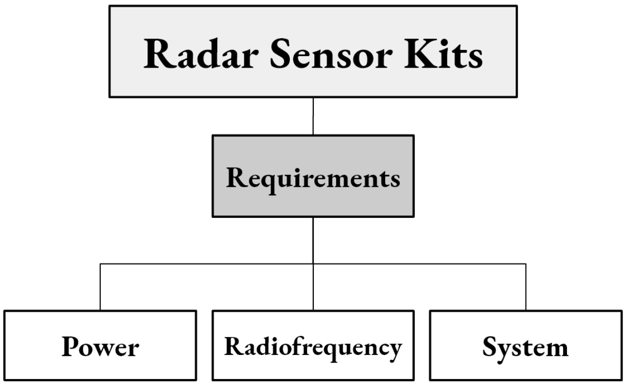


Figure 3.5: *Problem breakdown regarding the choice of radar development kit.*

To simplify the choice of radar development kit, the requirements are divided into three categories, see figure 3.5. The categories are power, radiofrequency (RF) and system related characteristics, as seen in figure 3.5. These three areas each have correlated specifications listed below. All of these attributes of the radar have each been assigned a weight from one to five based on its significance. A low score means little significance and a high score means the metric is important.

3.3.1 Power

Most of Verisure's products are wireless and battery powered, which make them easy to implement into larger systems. The number of batteries in the battery pack differs depending on the product it powers. The proposed radar product in this report will hence use a battery pack of six AA batteries, which was the maximum limit recommended by Verisure. In the pack, two sets of three batteries are connected in series and the two sets in parallel.

The aim for this product is to keep the power consumption as low as possible. This will allow for a longer lifespan for the battery pack. The metrics reviewed are related to how much power the radar system consumes in different operating states and the delay from different states to first measurements.

As seen in table 3.3 below, the time to first measurement from sleep mode/off mode is regarded as very important if the PIR would operate as the primary sensor and the radar as a secondary. This is to make sure that a target can not be missed due to a slow starting radar. The power consumption with default settings is included to give a ballpark estimate. The system voltage also has a great impact on the configuration of batteries and the capacity, as the power consumption is the product of the current and the voltage.

Table 3.3: *Power specifications.*

Metric	**Weight**
Power consumption default settings	4
Time from sleep to first measurement*	5
Time from power on to first measurement**	5
System voltage	2

**Regarded if the radar is in sleep mode before activated. **Regarded if the radar is in off mode before activated.*

3.3.2 Radiofrequency

As stated in section 3.1, Verisure requires that the FoV must cover an eight by eight square with the sensor positioned in one of the corners. This corresponds to a range of at least 11.3 m and a 90° angle of view. A target moving with a speed between 0.1 and 2 m/s must be detectable. These three metrics are essential for the concept and hence assigned the highest weight.

Using radar technology, speed, direction of movement, distance to target, distinguishing two or more individual targets and even a radar image may be available, depending on the radar type. For this project, only speed and direction of movement are considered ”nice to have”, as it adds to the understanding of the target movement. The ability to distinguish multiple targets and the distance to the target are not considered necessary for this radar application.

The radiofrequency specifications are presented in table 3.4

Table 3.4: *RF specifications*

Metric	**Weight**
Range	5
Speed of target	5
Field of view	5
Speed data	1
Direction data	1

3.3.3 System

The metrics related to the system listed in table 3.5 include the physical size of the antenna and the number of transmitters and receivers. The baseboard size is irrelevant as Verisure most likely will develop a proprietary baseboard but the antenna will be bought off the shelf, and thus has a fixed size. The antenna needs to be small enough to fit into a normal sized Verisure product.

The operating temperature is a critical requirement and thus assigned the highest weight. The predefined programs and functionality metric is considered in order to allow for testing and programming of the development kits, and also to secure the possibility of building a prototype.

Table 3.5: *System specifications*

Metric	**Weight**
Size of antenna	3
Number of transmitters and receivers	3
Operating temperature	5
Predefined programs and functionality	2

3.3.4 Manufacturer's data

Table 3.6 contains information provided by the two manufacturers of their respective development kit.

3.4 Final Selection

In order to evaluate and compare the two development kits, a scoring matrix is used. By weighting the metrics from one to five, five being the most important, and multiplying the weight with the score for each development kit, they can be compared to each other. The scoring of the development kits ranges from one to five, with five resembling characteristics close to the optimal. This means that characteristics that are better than what is specified does not necessarily receive a higher score. The further away from this optimal value, the lower the score.

3.4.1 Use Case

Based on the data in table 3.6, it is not realistic to completely replace the PIR with a radar. The power consumption of Infineon's radar, i.e. most efficient of the two, is roughly 6 mW and the power consumption for the PIR is approximately 0.2 mW according to Verisure. 6 mW corresponds to a battery life time of approximately a year and a half, based on the use of six AA-batteries and 40% in an armed state (based on data and calculations in section 4.2.9). This means it is not realistic to use the radar as the primary sensor of a battery powered system. Neither one of the two chosen development kits have a sleep state or settings allowing for a low power idle state. Hence, this is not further considered as an alternative. This leaves the option of having the radar as a secondary sensor in an off state activated by the PIR wherever it senses motion. This set-up will hopefully be power efficient enough to allow for the three year battery life demanded by Verisure.

Table 3.6: *Specifications for the Infineon Sense2GoL Pulse and Texas Instruments IWR6843ISK [12] [29].*

Specification	**Infineon Sense2GoL Pulse**	**Texas Instruments IWR6843**
General		
Frequency band	24-24.25 GHz	60-64 GHz
Bandwidth	0.25 GHz	4 GHz
Waveform	Pulsed fixed frequency CW	Pulsed FMCW
Measurable data	Speed, direction	Speed, direction, distance to target, distinguish multiple targets
Antenna	Separate, 1 transmitter, 1 receiver	Separate, 3 transmitters, 4 receivers
Operating temperature	-40 - 85	-40 - 105
Certifications and spectrum limitations	Free to use	Free to use
Power		
Power consumption default settings	6mW @ 6.7 Hz, 114 ms active frametime	216mW @1 Hz, 10ms active frametime
Time from power on to first measurement	1000 ms	50 ms
System voltage	5 V	3.3 / 1.8 V
Radiofrequency		
Range	20 m	25 m
Field of view	h: 80, v: 29	h: 108, v: 44
Maximum detectable speed	3 m/s	Adjustable, up to 55 m/s
System		
Antenna size	18*22 mm	20*25 mm
Operating temperature	-40 - 85 °C	-40 - 105 °C
Predefined programs and functionality	Developer's own GUI, Arduino compatible, USB, UART	Matlab GUI, USB, UART, I2C

3.4.2 Decision Matrix

As seen in table 3.7 below, Infineon's sensor scores a total of 134 points out of 205, compared to TI's 117 points. Therefore, Infineon's Sense2GoL Pulse is the sensor of choice and will be further evaluated.

In short, the performance of TI's sensor surpasses the target specifications too far to be the best option. It outperforms the requirements for range and FoV at the cost of a high power consumption. This is the major factor that made Infineon's sensor the winner: its low power consumption in connection with a more appropriate performance. The one major disadvantage of the Infineon sensor is the time from off-state to first measurement; however, in comparison with the overall performance of TI's radar, this flaw is not enough to discard the Sense2GoL Pulse.

Power

The most significant difference between the two sensors is the power consumption. Looking at the numbers in table 3.6, the power consumption with default settings for the Infineon sensor is approximately 6mW compared to TI's 216mW. Despite a higher sampling frequency and a longer active frame time of the Infineon sensor, the TI radar consumes about 36 times more power. This is likely because of the higher carrier frequency, the frequency modulation and the use of a phase-locked loop for frequency stabilisation.

Still, the Infineon's Sense2GoL Pulse is not ideal. The power consumption is very high compared to a PIR sensor that averages 0.2 mW, thus the choice of having the PIR as a primary sensor and the radar as a secondary sensor.

Having the radar in an off mode, the time from power on to first measurement is an important factor. There is a great difference between the radars here, where TI's sensor is up and running after 50 ms, while Infineon's require a whole second.

Radiofrequency

Studying the RF metrics, the TI sensor performs a lot better than the Infineon one. It has a longer range, a wider FoV and can detect faster moving targets than Infineon's radar. This does result in a poor score for TI's radar though, since it performs a lot better than required. Infineon's sensor does, by all means, perform worse but is also a lot closer to the desired performance.

Both sensors provide data on speed and direction of movement.

System

The antenna size of TI's sensor is slightly larger than Infineon's despite smaller aperture for the array elements. The three transmitter arrays and four receiver arrays are more than necessary, as only one of each is used in order to keep power consumption low. Infineon only has one of each and though they are bigger in size, the set up is more appropriate for this application.

Table 3.7: Scoring matrix.

		Ideal Score		**Infineon Sense2GoL Pulse**		**TI IWR6843**	
	Weight	Score	Total	Score	Total	Score	Total
Power							
Power consumption default settings	4	5	20	4	16	1	4
Time from power on to first measurement	5	5	25	2	10	4	20
System voltage	2	5	10	3	6	4	8
RF							
Range	5	5	25	4	20	3	15
Detectable Speed	5	5	25	4	20	2	10
Field of View	5	5	25	1	5	3	15
Speed Data	1	5	5	5	5	5	5
Direction data	1	5	5	5	5	5	5
System							
Size of Antenna	3	5	15	3	9	3	9
Number of RX and TX	3	5	15	5	15	1	3
Operating Temperature	5	5	25	3	15	3	15
Predefined programs and functionality	2	5	10	4	8	4	8
Total			**205**		**134**		**117**

The required operating temperature is covered by both sensors, and they are given the same score. Both sensors come with a GUI and allow for development of simple programs that may be useful in the event of a prototype build.

3.5 Infineon Sense2GoL Pulse

As mentioned in the introduction, the radar chip is the focus of the evaluation and not the baseboard, as Verisure most likely will develop their own baseboard with the desired specifications. Throughout the experiments and the evaluation of the Infineon radar sensor, the baseboard provided as part of the Sense2GoL Pulse kit is used for simplicity and time management reasons.

3.5.1 GUI and Adjustable Parameters

Infineon's Sense2GoL Pulse baseboard utilise an ARM Cortex-M4 microcontroller for signal processing. The provided graphical user interface (GUI), which can be seen in figure 3.7, displays settings and data. On the left side of figure 3.7, there are several adjustable parameters which all have an influence over the power consumption. The system settings that can be configured are the following:

- Pulse width
- Sampling frequency
- Samples per frame
- Sample skip count
- Frame rate

The pulse width, which is displayed in figure 3.6, is the duration of a single pulse. The intervals between the pulses is the sampling frequency. The total number of pulses during the frame time are samples per frame and the frame rate is the number of frames per second. The sample skip count is the number of samples to be skipped in each frame to get rid of the direct current offset in the I and Q signals. These are displayed as pink pulses in figure 3.6 [9].

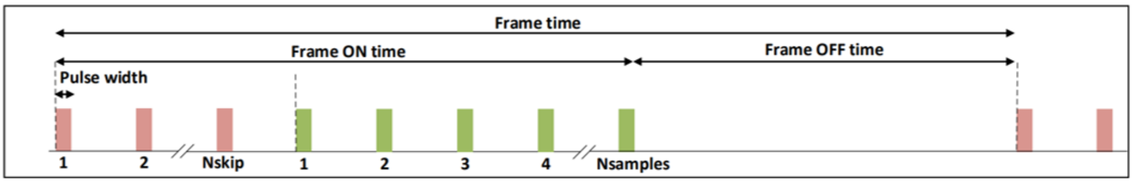
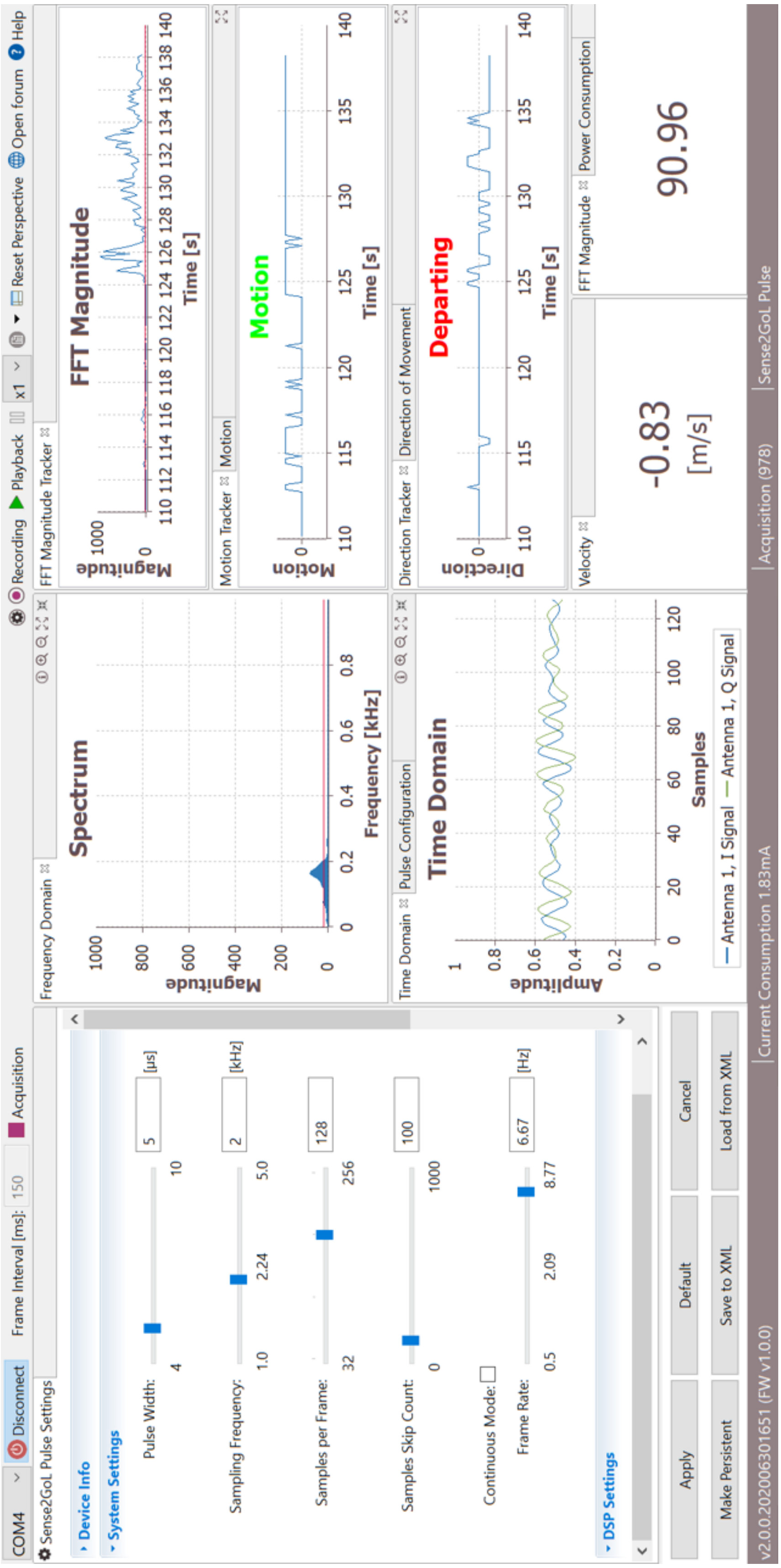


Figure 3.6: *Frame structure and terminology. Figure from [7].*



Frame Interval [ms]: 150

Pulse Width: 5 [µs] (4 – 10)

Sampling Frequency: 2 [kHz] (1.0 – 2.24 – 5.0)

Samples per Frame: 128 (32 – 256)

Samples Skip Count: 100 (0 – 1000)

Frame Rate: 6.67 [Hz] (0.5 – 2.09 – 8.77)

Velocity: -0.83 [m/s]

Power Consumption: 90.96

Figure 3.7: Infineon's graphical user interface.

The provided software also gives the user the ability to adjust some digital signal processor (DSP) parameters, such as motion and direction sensibility and the minimum and maximum detectable velocity. The sensitivity level is a manually set FFT magnitude threshold (i.e. the peak value of the signal) that needs to be exceeded for the software to indicate that motion has been detected. This sensitivity level can be set between 1-2000 in the GUI.

The GUI provides a lot of data and information in real time, as seen in figure 3.7. The FFT magnitude in the frequency and time domain and the amplitude in the time domain are displayed in three separate diagrams. The GUI also contains a graph indicating motion: that the threshold was passed. Target information such as if the target is approaching or departing, what velocity the target is moving at and the current consumption is displayed [7]. A detected motion is indicated both in the GUI and the LEDs on the radar baseboard, which light up in blue. In the tests and analyses of the radar sensor, this GUI is used to read and record these values.

3.5.2 Circuitry and Fundamental Features

A block diagram of the baseboard and radar chip is pictured in figure 3.8. A voltage controlled oscillator is utilised in order to keep the transmitted frequencies within the frequency band. A proportional to absolute temperature (PTAT) voltage source tunes the voltage depending on temperature. Doing this eliminates the need for a phase-locked loop or a microcontroller on board, which are both power consuming.

The intermediate frequency in-phase (IFI) and quadrature (IFQ) signals, which are output from the BGT24LTR11 radar chip, are connected with two single pole single throw (SPST) switches and their respective capacitor. During the sampling time, the capacitors are charged to the value of the input analogue signal and then the chip is turned off. This sample and hold process is controlled by a signal from the baseboard. The intermediate frequency signal is amplified and filtered at the baseband section before the analogue-to-digital converter (ADC) on the base board samples the signals.

The board and radar chip can be powered by an external power supply, providing 7V, a battery providing 5V or by the micro-USB port, also providing 5V. The use of several low-dropout regulators (LDO) changes the provided voltage to a stable 3.3V used by the electronic components on the baseboard and chip. The radar chip is supplied via a PMOS transistor, allowing the chip to be turned on and off during the sample and hold cycles. The current consumption of the radar chip is measured on the baseboard using a shunt resistance, which provides accurate data. The consumption is displayed in the GUI in figure 3.7 [12].

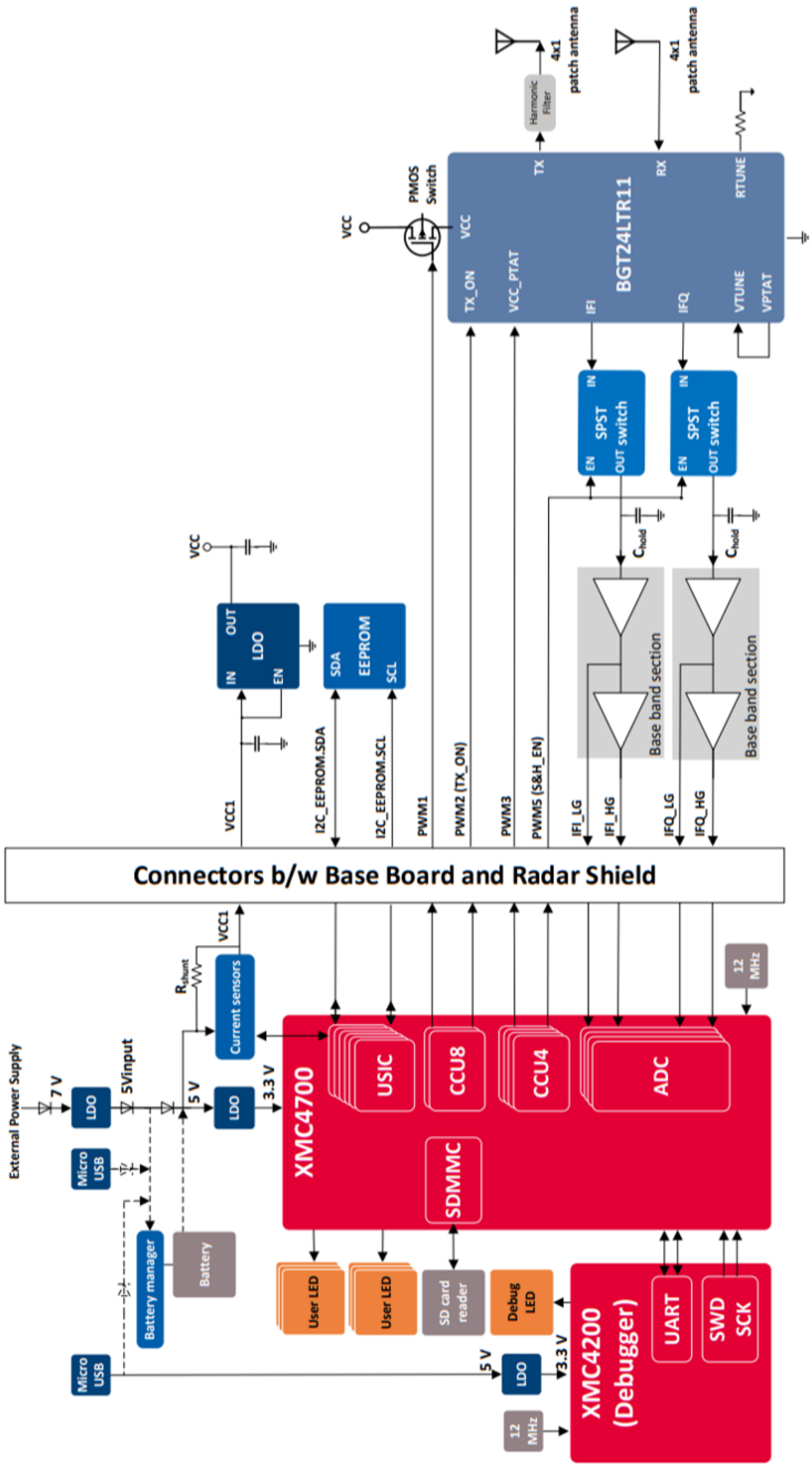


Figure 3.8: *Block diagram of baseboard and radar chip. Figure from [12].*

4. Experiments

In this chapter, nine experiments are presented, all created with the intention of increasing the understanding of the limits and possibilities of the radar sensor. The tests are based on the list of specifications, the critical requirements and the intended outdoor use.

4.1 General Test Set-up

Most experiments are conducted with this general set-up. If this set-up is not applied, it is be clearly pointed out in the experiment description.

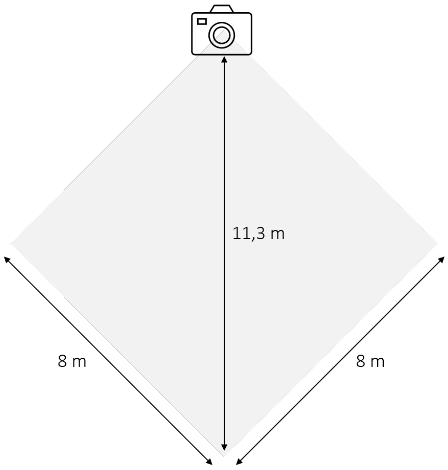


Figure 4.1: *The test area.*

The experiments are conducted indoors, in order to control the testing conditions. The test area is eight by eight meters, with the sensor in a corner as shown in figure 4.1. This means the diagonal across is 11.3 meters. This is also the minimum requirement for FoV of the radar. The sensor is mounted on a 3D printed mount and placed on a wooden pole at a height of 2.3 meters with a 20^o angle, seen in figure 4.2. The default settings of the sensor are used for all tests using the general set-up, except the output power and performance test. The settings are shown in table 4.1 below. The DSP algorithm in the provided software from Infineon has adjustable settings: the sensitivity threshold is set to 4/2000.

Table 4.1: *Default sensor settings.*

	Pulse width	**Sampling frequency**	**Samples per frame**	**Frame rate**
Default settings	5 μs	5 kHz	128	6.67 Hz

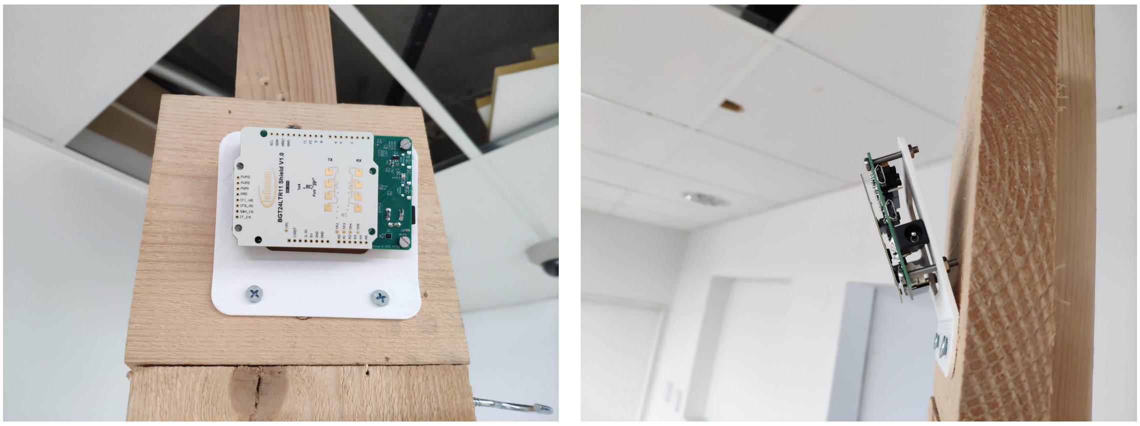


Figure 4.2: *Sensor mount.*

The tester (if the experiment requires one), pictured in figure 4.3, is dressed in clothes covering everything but the face to simulate the look of a burglar. The tester is 180 cm and weighs 70 kg.

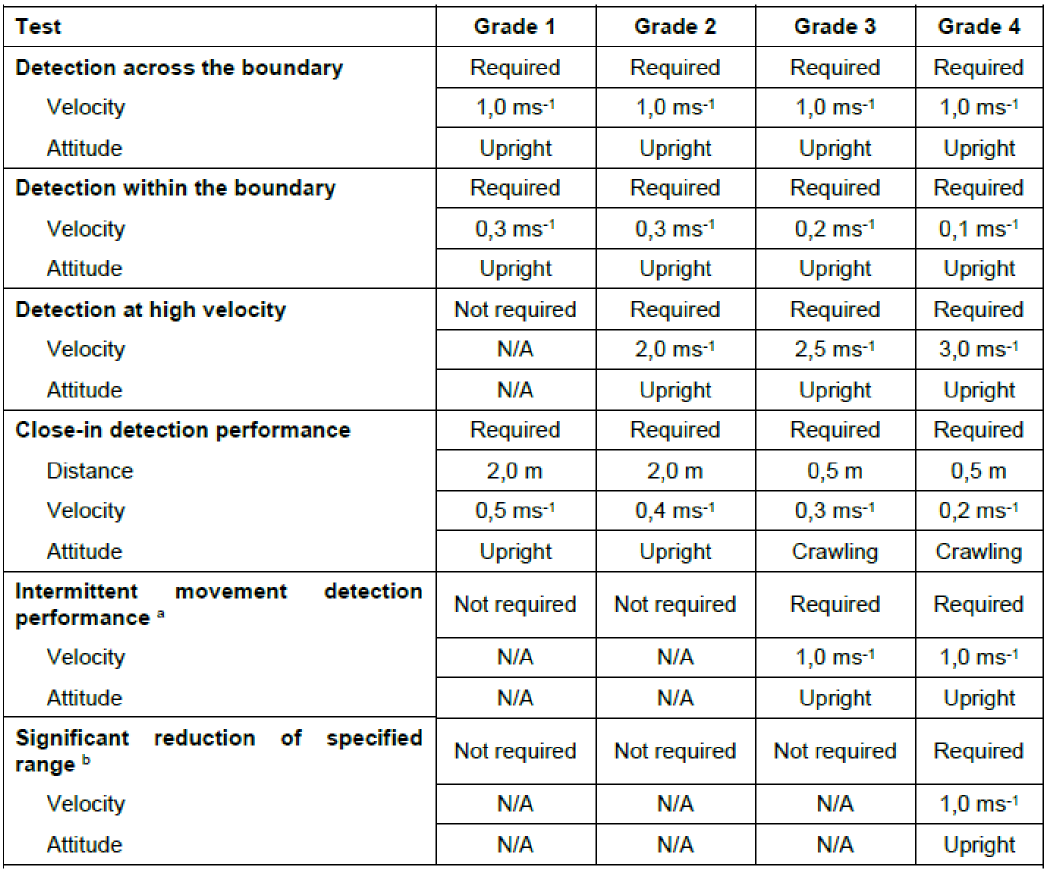
Figure 4.3: *Gustaf, the tester.*

4.2 Experiments

4.2.1 Test According to EN 50131-2-2

Background

Verisure's PIR sensor is required to pass the tests described in the EN standard 50131-2-2 for PIR based alarm systems of grade 2 (see figure 4.4). The EN standard is formulated by the European Committee for Standardization and is a document that contains the rules and guidelines which alarm systems containing a PIR must follow.



Test	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**
Detection across the boundary	Required	Required	Required	Required
Velocity	1,0 ms^{-1}	1,0 ms^{-1}	1,0 ms^{-1}	1,0 ms^{-1}
Attitude	Upright	Upright	Upright	Upright
Detection within the boundary	Required	Required	Required	Required
Velocity	0,3 ms^{-1}	0,3 ms^{-1}	0,2 ms^{-1}	0,1 ms^{-1}
Attitude	Upright	Upright	Upright	Upright
Detection at high velocity	Not required	Required	Required	Required
Velocity	N/A	2,0 ms^{-1}	2,5 ms^{-1}	3,0 ms^{-1}
Attitude	N/A	Upright	Upright	Upright
Close-in detection performance	Required	Required	Required	Required
Distance	2,0 m	2,0 m	0,5 m	0,5 m
Velocity	0,5 ms^{-1}	0,4 ms^{-1}	0,3 ms^{-1}	0,2 ms^{-1}
Attitude	Upright	Upright	Crawling	Crawling
Intermittent movement detection performance [a]	Not required	Not required	Required	Required
Velocity	N/A	N/A	1,0 ms^{-1}	1,0 ms^{-1}
Attitude	N/A	N/A	Upright	Upright
Significant reduction of specified range [b]	Not required	Not required	Not required	Required
Velocity	N/A	N/A	N/A	1,0 ms^{-1}
Attitude	N/A	N/A	N/A	Upright

Figure 4.4: *General walk test velocity and attitude requirements [30].*

There are also requirements of the atmospheric conditions during the tests.

- Temperature: 15 - 35°C
- Relative humidity: 25% to 75% RH
- Air pressure: 86 - 106 kPa [30]

To accommodate for these test requirements, Verisure has created a detailed test plan for the PIR sensor. The test plan also includes tests that are not specified in the EN requirements, but provide Verisure with valuable information about the PIR device's performance. The radar sensor is put through the same test procedure that covers both the EN standard and the more complex test cases. The test described in *Method* is the actual test plan used by Verisure for PIR sensors. As there is internal data available of the PIR performance, the results can be compared.

Aim

To analyse the performance of the Infineon Sense2GoL Pulse radar sensor in a Verisure developed test including the EN standard test for PIR sensors.

Method

In this experiment, four scenarios are tested:

- Walk (1m/s)
- Crawl (0.5m/s)
- Belly crawl (0.3m/s)
- High velocity walk across room (2m/s)

See appendix A.2 for movement demonstrations. The tester walks or crawls both from the right and from the left, in lines across the FoV with increments of one meter, as shown in figure 4.5. For the high velocity test, the tester walks parallel to the test area boundaries, straight across towards the sensor, once from right and once from the left (the walk pattern is shown in appendix A, figure A.1d). The tester enters the FoV at the respective speeds.

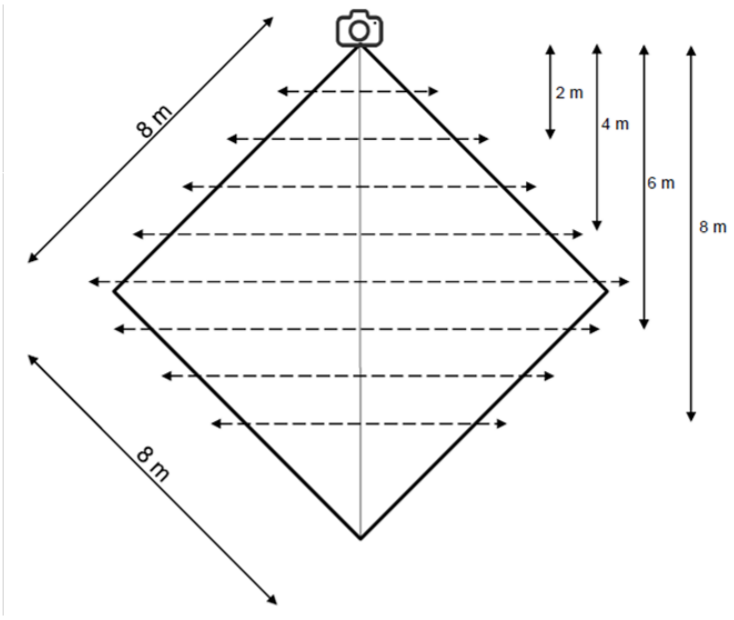


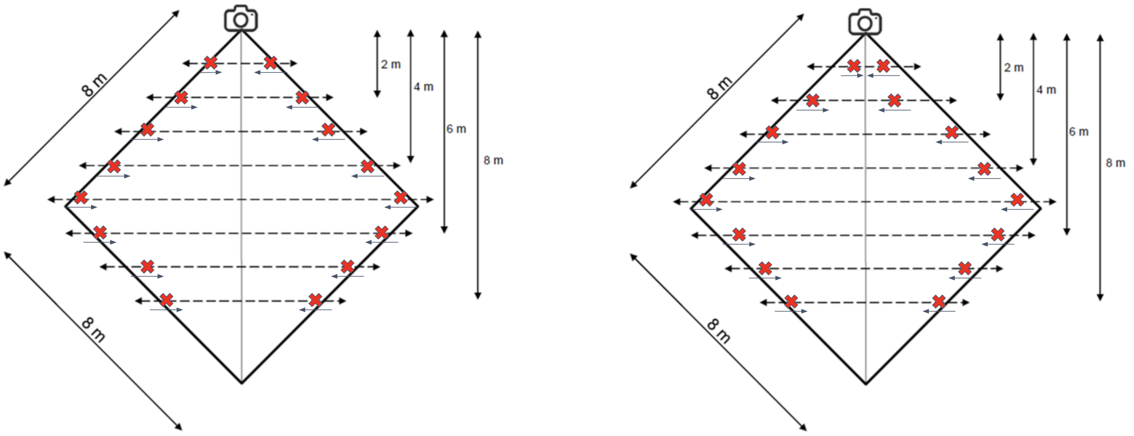
Figure 4.5: *Movement pattern for walk, crawl and belly crawl test [31].*

An observer marks the position of the tester when the radar is triggered. The area in between is interpreted as the detection area.

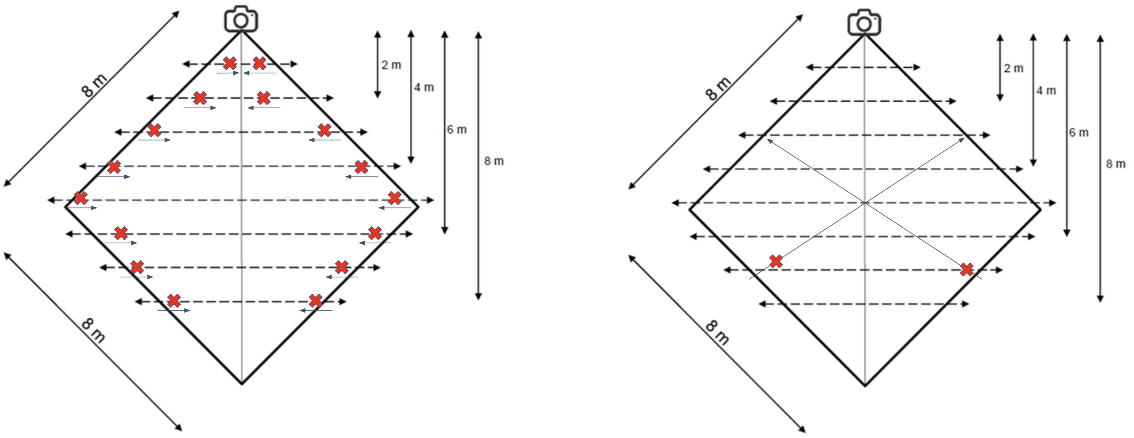
Essentially, the EN certification only requires a walking or "upright" position at these speeds and distances. This means that passing the crawling and belly crawling tests is not strictly required.

Results

The conditions were stable during the experiment with a temperature between 23.1-24.8°C and a humidity ranging from 45 % to 50 %. The experiments were carried out at sea level and the air pressure was 101 kPa. The data originates from a portable weather station and the Swedish Meteorological and Hydrological Institute's weather forecast at the time.



(a) *Walk.* ***(b)*** *Crawl.*



(c) *Belly crawl.* ***(d)*** *High velocity.*

Figure 4.6: *EN standard tests for the Sense2GoL Pulse. Detection of the tester is marked with a red cross and the accompanying arrow illustrates in what direction the tester was moving.*

Notable in figures 4.6b and 4.6c is the position of the tester when detected. At the one and two meter range, the tester managed to get much further into the FoV than when standing up, or when crawling/belly crawling at a greater distance from the sensor.

Compared to the EN test results for the PIR, it is obvious that the radar triggers a lot earlier than the PIR. The radar performance in the walk test is similar to the walk test results of the PIR. In the crawl and the belly crawl tests, the radar performs a lot better than the PIR with faster and more accurate detections. The PIR test graphs cannot be published due to an NDA. There are no undetected passings at all in the radar test. This means the radar passes the EN certification test, and also Verisure's added test cases.

The high radar sensitivity should be taken into account, though. The threshold is set to be very low: the radar triggers when the magnitude of the signal is above 4/2000.

4.2.2 Sensitivity Level

Background

In order to evaluate what the most appropriate sensitivity threshold is, multiple levels are compared and evaluated. The threshold used for the general test set-up is 4/2000, which in a preparatory test was the lowest level possible while still avoiding false radar triggers. This test illustrates what impact the threshold has on detection sensitivity and gives a ballpark figure of what a suitable threshold is.

Aim

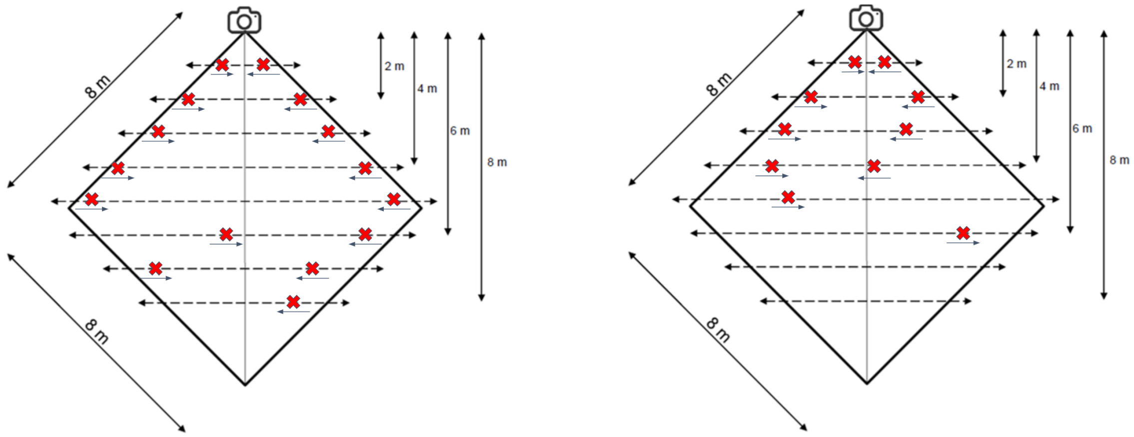
To gather data on the detection speed and accuracy at different sensitivity level thresholds of the radar sensor, based on indoor walk tests.

Method

The general test set-up is applied for this experiment. The test is performed twice, first with a threshold of 10/2000 and then with a threshold of 20/2000. An observer marks the position of the tester when the radar is triggered. The test result presented in 4.2.1, figure 4.6a is also included in the analysis. Because the test set-up is exactly the same as for the EN standard walk test, no new test applying the 4/2000 level is conducted.

Results

The two graphs in figure 4.7 can be compared to the results shown in figure 4.6a (radar walk test, 4/2000). As seen in 4.7b, a sensitivity level of 20/2000 resulted in a poor rate of detection at distances further than four meters from the sensor. In the walk test where the threshold was set to 10/2000, the tester was detected at a similar point as in figure 4.6a at a range of five meters and closer. At ranges greater than five meters, the radar struggled to detect the tester, especially at distances above six meters when the tester walked from left to right.



(a) *Sensibility threshold 10/2000.* ***(b)*** *Sensibility threshold 20/2000.*

Figure 4.7: *Walk test with different threshold.*

4.2.3 Fast Fourier Transform Magnitude Analysis

Background

This experiments aims to increase the knowledge of the radar's signal behaviour. Collecting data of the FFT magnitude during walk tests at different ranges gives a good understanding of how the signal behaviour changes with target distance.

Aim

To analyse the FFT magnitude of a walking target at varying ranges.

Method

The tester walks (1 m/s) across from the left, stops and then returns from the right across the test area. This is done at three different distances from the radar; one, four and eight meters. See figure 4.5 for reference. Apart from the walk patterns, the procedure is the same as described in the general test set-up (section 4.1).

Results

At one meter, the signal is strong, peaking at 166.9. The crossings are clearly recognisable in the plot in figure 4.8.

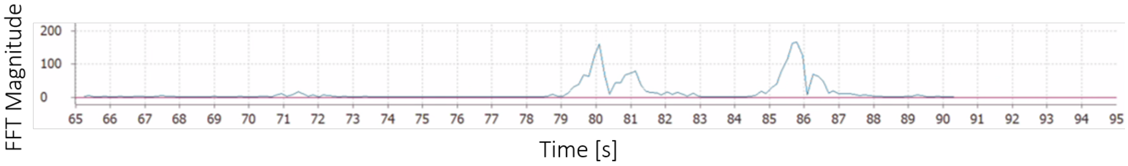


Figure 4.8: *1 m.*

The signal is significantly weaker at four meters: 56.47 at most. Yet, the two crossings are distinguishable, see figure 4.9.

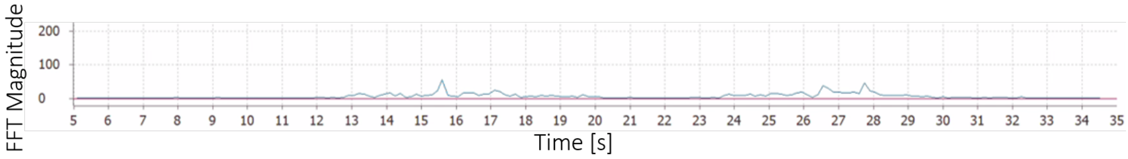


Figure 4.9: *4 m.*

At a distance of eight meters, the signal did not once pass 20, only 18.72 is registered, see figure 4.10. The first crossing lasted between second 29 and 36, at around 41 the tester started walking again and finished at second 48.

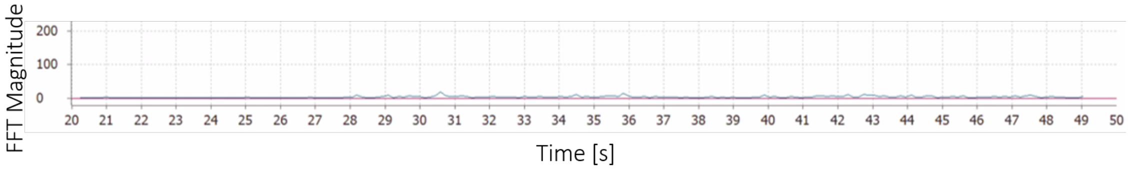


Figure 4.10: *8 m.*

4.2.4 Velocity

Background

To gather more data on how the detection performance depend on the velocity of a human target, a velocity test is conducted.

Aim

To investigate the speed limits of a moving human target of the radar sensor, both the lower and upper limit.

Method

These scenarios are tested:

- Very slow walk (0.2 m/s)
- Slow walk (0.5 m/s)
- Walk (1 m/s)
- Jog (3 m/s)
- Run (4.5 m/s)
- Dash (6 m/s)

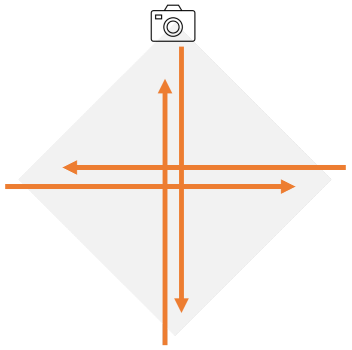
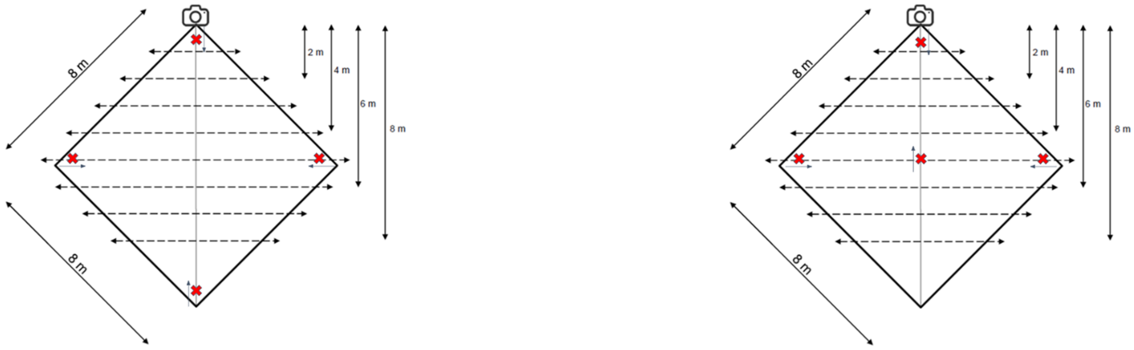


Figure 4.11: *Movement pattern for the velocity test.*

The tester runs once at every speed: straight towards the sensor, away from it, across from the right and from the left according to figure 4.11. The movements across is at a distance of five meters from the sensor. Apart from this, the general test set-up is applied. If the sensor is triggered at any time during, or in direct connection to the target movement, the scenario is defined as detectable. An observer records the position of the tester when the radar triggers.

Results

(a) *Very slow walk, 0.2 m/s.* ***(b)*** *Slow walk, 0.5 m/s.*



(c) *Walk 1 m/s.* ***(d)*** *Jog, 3 m/s.*

(e) *Run, 4.5 m/s.* ***(f)*** *Dash, 6 m/s.*

Figure 4.12: *Velocity test results.*

The detection of slow movements was very fast, see figure 4.12a, 4.12b and 4.12c. When reaching jog speed (figure 4.12d), the detection of the tester coming from the right, from the left and from behind the sensor was as fast as before; however, the tester got very far into the FoV before being detected when moving straight towards the sensor. The results are similar for run and dash speed, see figure 4.12e and 4.12f. It should be noted that the top detectable speed according to the data sheet is 3 m/s for this sensor, which in this test corresponds to a jog.

4.2.5 Use Case

Background

As the radar sensor is assessed to be too power consuming to work on its own, a PIR sensor will trigger the radar in order to get a a second confirmation of the movement that caused the PIR to trigger. As described in section 3.2, the radar will be off until it is woken by the PIR. According to Infineon, the wake-up time is about one second for the Sense2GoL Pulse.

Aim

To investigate the adequacy of the Infineon radar sensor in a set-up were the radar is off and then activated by the PIR.

Method

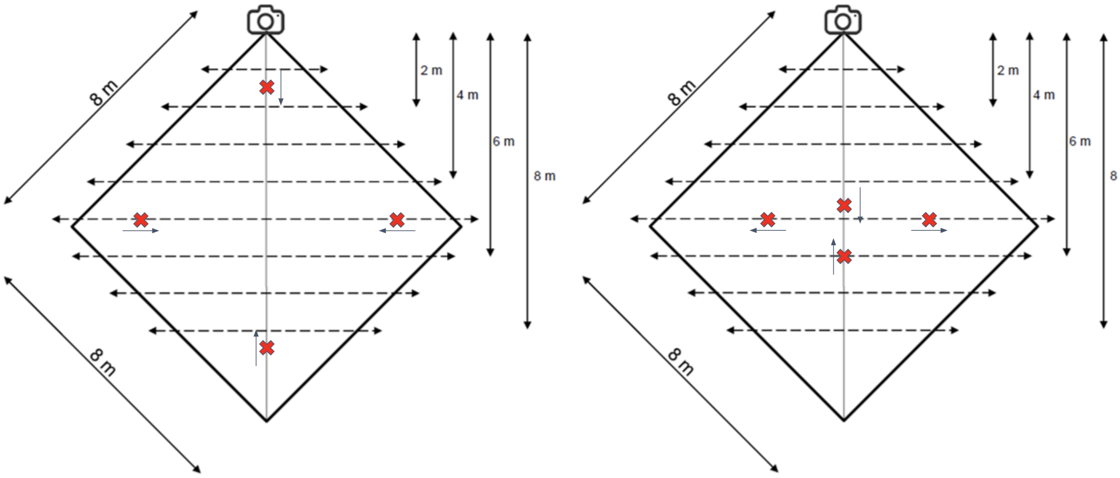
The tester moves across the FoV at two different speeds in the directions pictured in figure 4.11 in section 4.2.4:

- Walk (1 m/s)
- Run (4.5 m/s)

As the specified sensor wake-up time is about one second, any indications before one second has passed since the tester entered the FoV are ignored. Only detections after this time are registered and manually noted in a graph, same as used in the EN-test and shown in figure 4.5.

Apart from the movement pattern, the general test set-up is applied. An observer marks the position of the tester when the radar is triggered.

Results



(a) *Walk 1 m/s.* ***(b)*** *Run 4.5 m/s.*

Figure 4.13: *Detection graph from walk and run test with a detection delay of one second.*

The sensor passed both the walk and run tests seen in figure 4.13; however, figure 4.13b shows that the tester got three quarters of the way when running across before he was detected. This is not surprising though, as the target has a one-second lead on the sensor. While taking this delay into consideration, the radar sensor was still quick to respond just as in most of the previous tests.

4.2.6 Penetrative Ability

Background

Because this project is targeting outdoor usage, some tests of a simulated garden environment are conducted. Could a tree or some bushes prevent the radar from detecting a human? If parts of the house, or neighbouring houses, are within the FoV, could people walking inside trigger the sensor?

Aim

To investigate the penetrative ability of the radar sensor in order to map compatibility with different garden surroundings and benchmark it against a PIR sensor.

Method

Six different materials are set up to test the penetrative ability of the radar sensor:

- Plant foilage
- Cardboard wall
- Wooden pallet

- Glass window
- Metal door

First, the tester places himself behind a sheet or wall of the material in question, located five meters from the sensor, and stands completely still. When the sensor has stopped indicating movement, the tester moves his arms and legs for three seconds. If the sensor is triggered during, or in direct connection to the movement, the tester is detected and the material is interpreted as penetrable. The default radar settings are applies and the sensitivity threshold is set to 4/2000.

Results

Table 4.2: *Results of the penetrative ability test.*

Material/obstacle	Depth	Detection	Comment
Nothing	-	Detected	Reference, strong signal
Plant foilage	~400 mm	Detected	Weak signal
Cardboard wall	3 mm	Detected	Strong signal
Wooden pallet	20 mm	Detected	Very weak signal, single pulses
Glass window	Triple pane window	Detected	Very weak signal, single pulses
Metal door	55 mm	Not detected	Distance to object is 6 m

As seen in table 4.2, nearly all tested materials were penetrable but to a various degree. Cardboard has very little impact on the signal strength, while glass and wood blocked almost all RF energy. Metal however, was not penetrable. It should be noted that the distance from sensor to obstacle was one meter greater for the metal door than for the other materials. This was due to limitations at the test site. For photos of the test and the equipment used, see appendix B.

4.2.7 Outdoor Test

Background

To further investigate the effects of wind disturbances and similar sources of false alarms, a test in an outside environment is carried out. The aim is to provide a better understanding of these kinds of disturbances and how often they occur.

To check if a moving plant could trigger the sensor, an initial test was carried out indoors. The radar triggered on the moving plant in the indoor test, where there were no other possible triggers.

Aim

To evaluate the effects an outside environment has on the occurrence of false alarms caused by outside conditions and surroundings.

Method

The sensor is mounted in the same way as the previous tests: on a height of 2.3 m and an angle of 20°. The test site has got several different plants and it can be seen in figure 4.14. The horizontal distance from the sensor to the box is 460 cm. The box itself is 480x210cm.

Figure 4.14: *Outdoor test site, sensor is placed to the right in the picture, facing north.*

The software records for five minutes and indicates if a signal is above the sensitivity level threshold, by changing the motion value from zero to one. Also, the FFT magnitude of the signals are reviewed. This procedure is performed for three different sensitivity levels. First the sensitivity level is set to 4/2000, then 10/2000 and lastly 20/2000.

Result

At the time of the test, the 6th of August 2020, the temperature was 26^oC and the wind approximately four m/s according to the Swedish Meteorological and Hydrological Institute's weather forecast at the time.

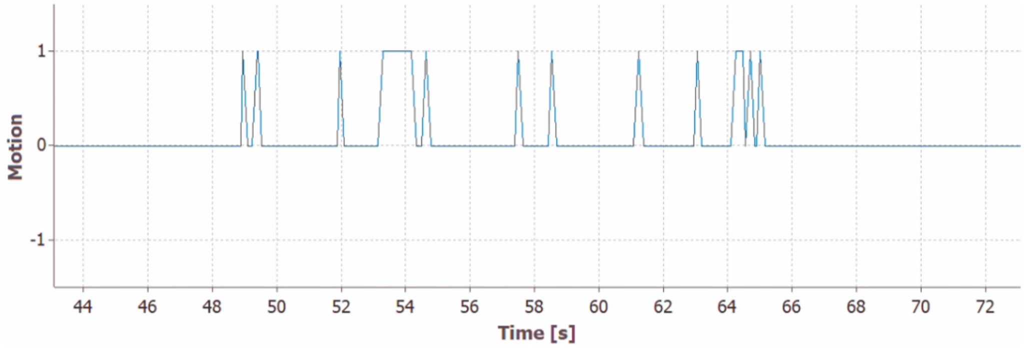


Figure 4.15: *Sensitivity 4/2000.*

When the sensitivity was set to a low level, such as 4/2000, the sensor triggers easily. Any slight movement of the plants or the tree caused the sensor to indicate motion. Figure 4.15 shows a representative 30 seconds out of the total five minutes.

The majority of these peaks have a magnitude of between four and six, with a few individual peaks reaching magnitudes of around nine or ten.

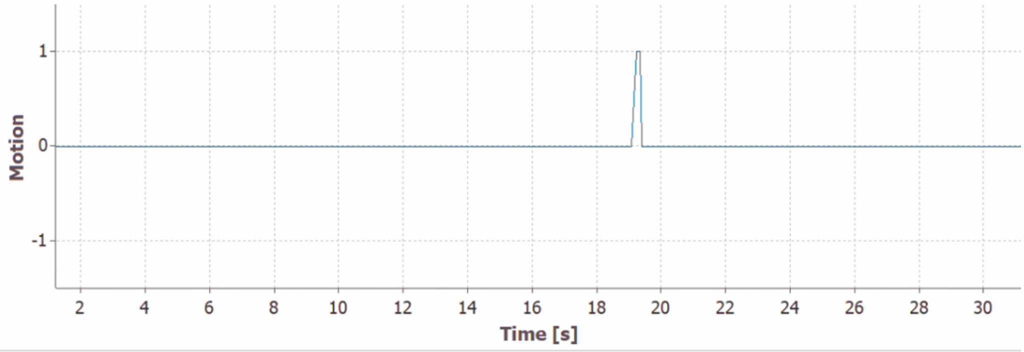


Figure 4.16: *Sensitivity 10/2000.*

Increasing the threshold undoubtedly decreased the number of triggers caused by wind disturbances. During the whole test at the 10/2000 level, there was only one trigger caused by the wind, seen in figure 4.16. The magnitude of this pulse was just above ten.

When the threshold was set to 20, no triggers due to wind disturbances were recorded. Because the test site was just in front of a side entrance of an office building, a few people passed by the sensor on their way in or out of the office. This was taken advantage of and their time of passing was noted. In figure 4.17, a person passed by the sensor at a distance of approximately three meters. The signal magnitude recorded was between 20 and 90.

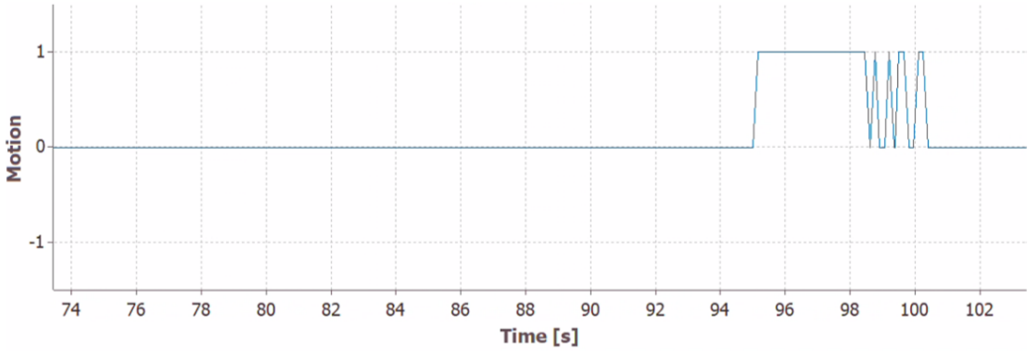


Figure 4.17: *Sensitivity 20/2000 with person passing by.*

4.2.8 Output Power and Performance

Background

In order to optimise the power consumption of the radar sensor, the relation between the energy of the transmitted signal and the sensor performance is of great interest and is explored more in depth in this test.

The output power is directly connected with the energy of the transmitted signal and is determined by several factors that can be adjusted in the provided software from Infineon. The idea is to vary these factors to map the relationship between the output power and the performance of the radar. The GUI provided by Infineon can be seen in figure 3.7.

Aim

To determine the relation between output power and performance for the Infineon Sense2GoL Pulse.

Method

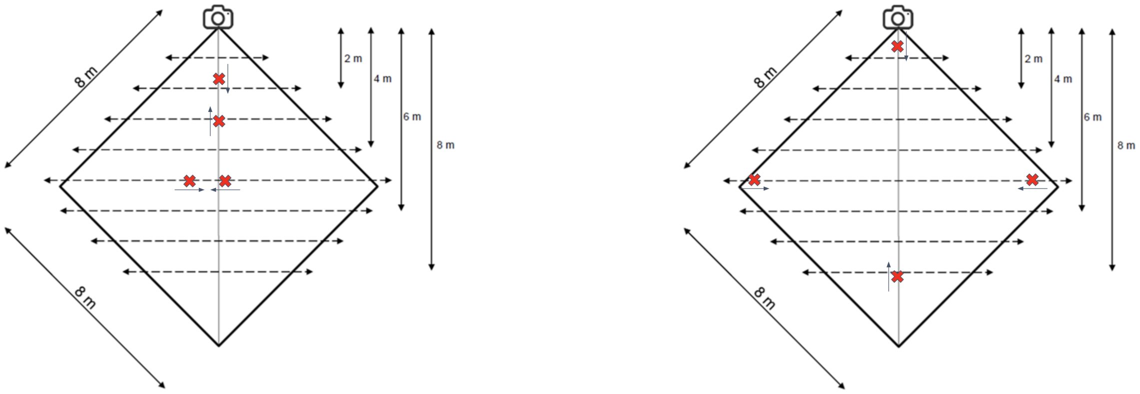
The tester walks, with a velocity of 1 m/s, across the FoV at a distance of five meters, once from the right and once from the left, just as in the velocity test, see figure 4.11. If the sensor is triggered at any time during, or in direct connection to the target movement, the scenario is defined as detectable. The position of the tester is manually recorded by an observer.

The radar operates in seven different states that correspond to varying power consumption, ranging from a state with as low power consumption as possible, to a reference state with the default settings. The remaining states are arbitrarily picked to demonstrate the influence of the different parameters and the signal energy. All settings for the different states are listed in table 4.3. The skip count is kept the same in all states to decrease the number of variables. Furthermore, the samples per frame parameter is kept at 128 except the first low power state, to make the test more comprehensible. Go back to section 3.5.1 for a thorough description of the adjustable parameters.

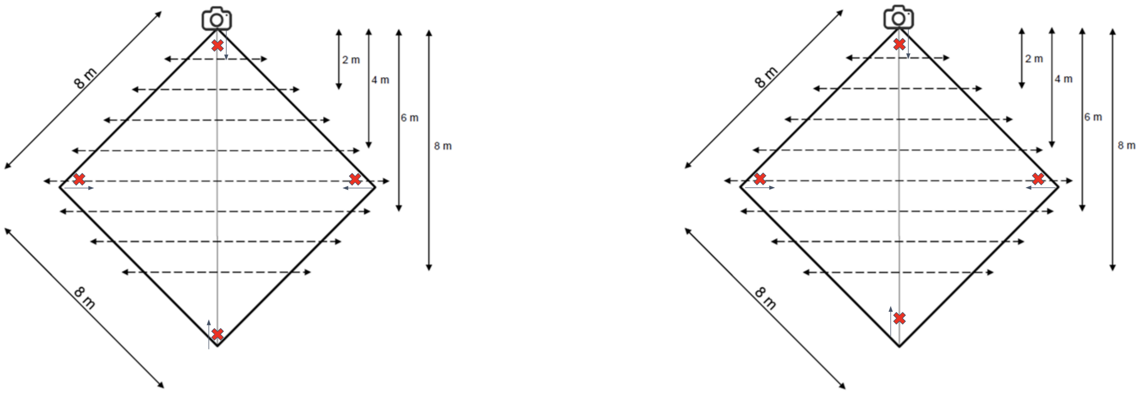
Table 4.3: *Different states with ranging power consumption*

	Pulse width	**Sampling frequency**	**Samples per Frames**	**Frame rate**	**Current**
State 1 (low power)	4 μs	1 kHz	32	0.5 Hz	0.45 mA
State 2	5 μs	5 kHz	128	3 Hz	0.7 mA
State 3	4 μs	2 kHz	128	4 Hz	1.19 mA
State 4	5 μs	2 kHz	128	4 Hz	1.23mA
State 5	5 μs	2 kHz	128	5 Hz	1.45 mA
State 6	5 μs	3 kHz	128	6.67 Hz	1.45 mA
State 7 (default)	5 μs	5 kHz	128	6.67 Hz	1.83 mA

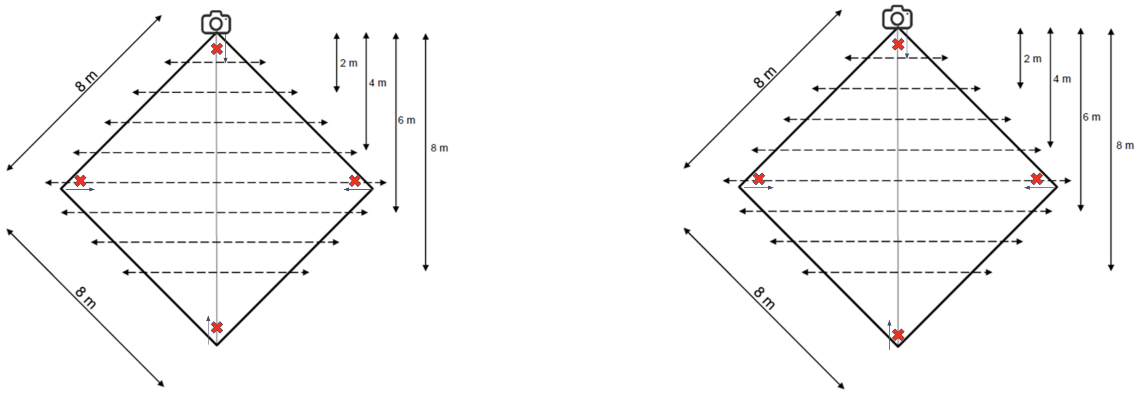
Result



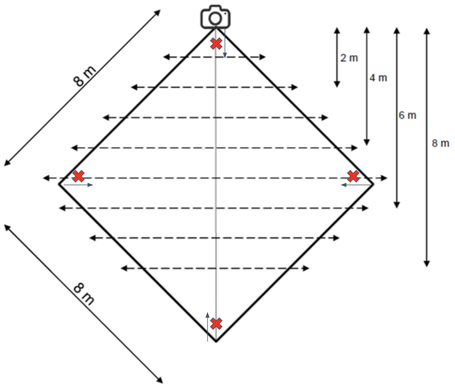
(a) *State 1.* ***(b)*** *State 2.*



(c) *State 3.* ***(d)*** *State 4.*



(e) *State 5.* ***(f)*** *State 6.*



(g) State 7, default.

Figure 4.18: *Test results from the seven different states.*

State 7 (figure 4.18g) is the default settings, used as a reference for the other tests. The radar was quick to notice any movement and the signal was steady and perceived as reliable.

The radar sensor was very slow to react in state 1 (figure 4.18a) to any movement and triggered very late, even though the tester was moving at the moderate speed of 1 m/s.

Operating in state 2 (figure 4.18b), the sensitivity level was raised to 10/2000 as it was continuously triggering at the default sensitivity level of 4/2000. When this change was made, the signals were strong and the sensor reacted quickly to the tester entering the test area. This state has a relatively low frame rate (3Hz) which likely is the main factor to the low current of 0.7mA.

The signal quality in state 3 (figure 4.18c) was perceived as somewhat slow and uneven. The sensor triggered fast but the signal was not as steady as in the default state. This could be a result of the decreased pulsed width.

In state 4 (figure 4.18d), the pulse width was slightly increased compared to state 3, and this made the signal appear more consistent. Just as before, the sensor was quick to trigger.

The frame rate was increased for state 5 (figure 4.18e), which resulted in a slightly greater current consumption but changed the behaviour of the received signal little. Similar to the change between state 1 and 2, it can be seen that the frame rate has a big influence on the power consumption.

State 6 (figure 4.18f) has the same power consumption as state 5, with the only difference that the sampling frequency and frame rate is increased. Yet, this did not increase signal behaviour. The signal was pulsing and triggering falsely, with nothing moving in the FoV.

The best performing state with the lowest power consumption was state 2, including the increased sensitivity threshold. The power consumption in this state is only 0.7 mA, compared to the default 1.83 mA.

4.2.9 Battery Lifespan Estimation

Background

The power consumption governs the battery lifespan and it is therefore necessary to investigate if the goal of having a battery lifetime of at least three years is achievable.

Aim

To provide an estimation on how long six AA lithium batteries would last in a radar integrated into a Verisure product containing a PIR and a camera.

Method

In the estimation, the radar will be in an off state and then activated when the PIR is triggered, as described in section 3.2. The system will be powered by six AA lithium batteries with a total capacity of capacity of 5880 mAh. The annual self discharge rate is estimated to 2%.

The assumption for this test is that the alarm system is disarmed 60% of the time and armed 40% of the time. In the estimation, the radar is considered active only when the alarm is triggered by the PIR, and remains active for as long as the camera is capturing and transmitting photos. The current consumption for the Sense2GoL Pulse radar with default settings is 1.83mA. The system can enter six states, which are listed below.

- Idle state, sleep mode where only PIR is active.
- Armed state, the alarm is armed.
- Day trigger, photos are taken and transmitted. Radar is active.
- Night trigger, photos are taken in dim lighting conditions and then transmitted. Radar is active.
- Day false trigger, pictures are captured and transmitted. Radar is active.
- Night false trigger, pictures are captured and transmitted. Radar is active.

The number of occurrences for each state is based on estimations provided by Verisure. To measure the average current in these six states, an Otii power analyser is used. To calculate the battery lifespan, the average current during one year is considered. This value is then used to estimate how many years the batteries would last and are used in equation 2.8.

Result

In figure 4.19 below, an example of current consumption for a product from Verisure is shown. When the alarm system was triggered in dim light conditions, the current peaks at 1.15A when the pictures were captured and then the current decreased during the transmission. This passage of events has an average current of 98.3 mA over a period of 17.7 seconds, which can be read in the top right corner of figure 4.19. After the pictures were transmitted, the system returned to the idle state.

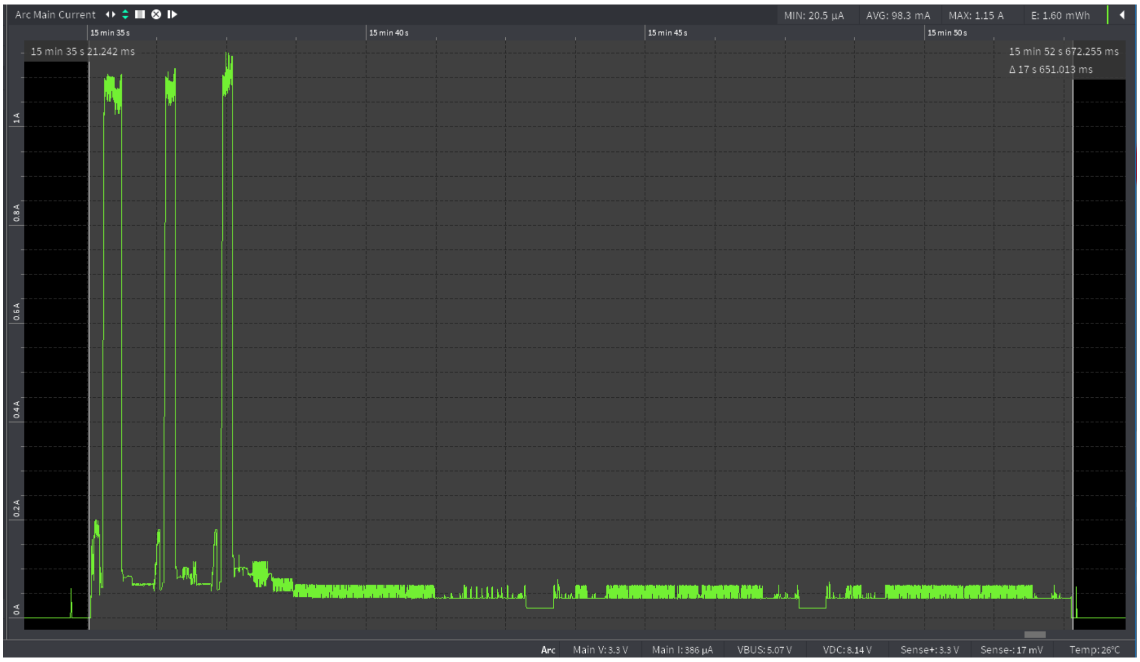


Figure 4.19: *Current plotted when alarm is activated and camera takes pictures and transmit them.*

The other states were tested in the same way as the night trigger state, with the help of the Otii power analyser. The average currents for the six states are presented in table 4.4 below.

Table 4.4: *States which the product can enter. The idle state is active all of the remaining time. The radar consumption is added whenever a trigger occurs.*

	Average Current	**Time**	**Occurrences (year)**	**Energy cons.**
Idle state	0.06 mA	-	-	525.23 mAh
Arm	35.3 mA	2.4s	730	17.18 mAh
Day trigger	67.6+1.83 mA	18.2s	24	8.42 mAh
Night trigger	98.3+1.83 mA	17.7s	30	14.93 mAh
False(day)	67.6+1.83 mA	18.2s	730	256.24 mAh
False(night)	98.3+1.83 mA	17.7s	365	181.67 mAh
Total				1003.66 mAh

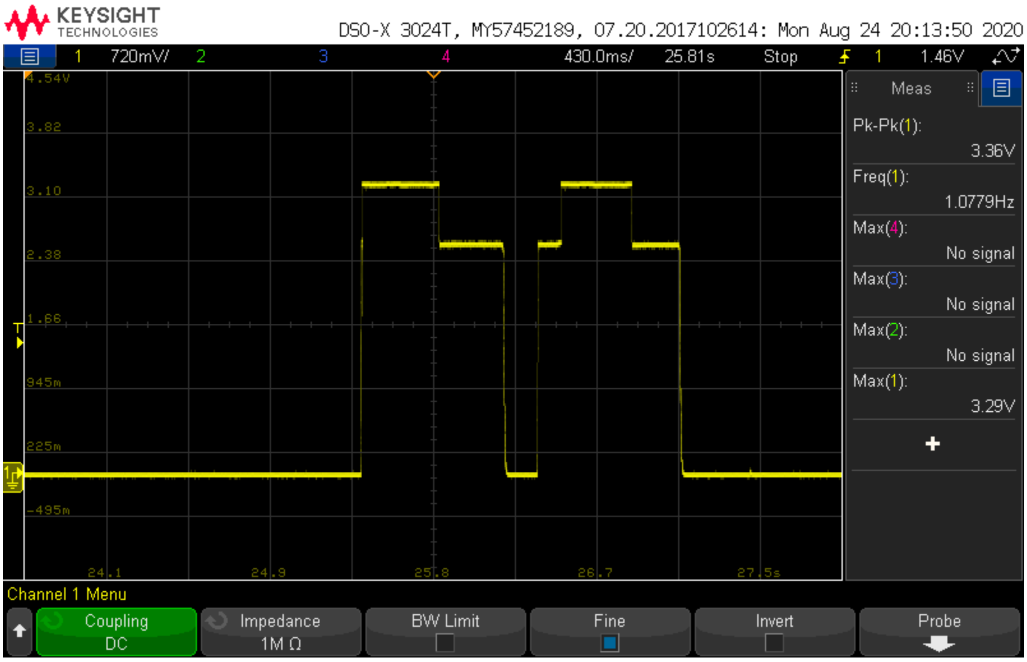
The total energy consumption for the product is 1003.66 mAh a year, as seen in table 4.4. A discharge rate of 2% results in an expected lifetime of 5.55 years, compared to an expected lifetime without the radar of 5.61 years meaning the difference is only about three weeks. This means that the requirement for battery lifetime is fulfilled and that the difference in power consumption between having the radar as a second opinion and not having the radar at all, is insignificant.

5. Prototype

In order to visualise and test the communication between the Cam-PIR3.5 and the radar sensor, a simple prototype is produced. The functionality is based on a use case were the radar is off and then activated when the PIR is triggered, as described in section 3.2.

5.1 Hardware

The Cam-PIR3.5 contains, as mentioned earlier, a PIR sensor and a camera. When the PIR sensor is triggered, three photos are captured in rapid succession. This activating signal, which starts the camera, will also be used to trigger the radar, allowing for photo evidence as well as radar data, such as speed and direction of movement.



DSO-X 3024T, MY57452189, 07.20.2017102614: Mon Aug 24 20:13:50 2020

Pk-Pk(1): 3.36V
Freq(1): 1.0779Hz
Max(4): No signal
Max(3): No signal
Max(2): No signal
Max(1): 3.29V

Coupling DC
Impedance 1M Ω

Figure 5.1: *Digital signal from the Cam-PIR3.5 when intruder is detected.*

This signal goes from low (∼0V) to high (∼3V) for short intervals of around 0.8-0.9 seconds when the PIR is triggered, see plot in figure 5.1. The activation signal is connected to a multipurpose input/output pin on the Arduino compatible base board, which is programmed to start the radar. The signal can be seen in figure 5.1 and was captured with an oscilloscope.

The Cam-PIR3.5 will be powered either by batteries or by an external power supply (3 V). The radar sensor will be powered through a micro-USB port to a computer. This is to allow for data acquisition and real-time feedback. Thus, a wire to cater for common ground is connected between the Cam-PIR3.5 and the radar board. It is also possible to power the radar chip from an external power supply, but this requires 7 V.

5.2 Software

The Infineon XMC4700 baseboard is built with Arduino compatibility allowing for development of simple programs.

Based on a code example, a program that allows the radar to start when the activating signal becomes high has been produced. Data from the radar is available in a GUI. Photos from the Cam-PIR3.5 camera and radar data can be combined and used for validation of the trigger cause.

The set-up has been slightly simplified, as the radar is not off in-between its active periods. The purpose of the prototype is to test the communication between the Cam-PIR3.5 and the radar sensor; to demonstrate how such a device could work. Thus, the radar will have power supplied at all times, but only be activated upon a signal from the PIR.

5.3 Sensor Packaging

In order to demonstrate what a Cam-PIR3.5-radar device might look like, as well as to give the prototype a more appealing look, a sensor house has been developed. The backboard and the lid were first drawn in Creo Parametrics and later 3D printed in ABS plastic.

5.3.1 CAD and 3D-printing

The prototype house pictured in figure 5.2 consist of the back plate with mounts for the Cam-PIR3.5 and the radar, and a lid with cut-outs for the camera, the PIR sensor and the light sensor. As the radar waves easily penetrate the thin plastic, no holes have been made for the antenna.

Figure 5.2: *The sensor house, with back plate and lid.*

Figure 5.3 shows the back plate. Its radar sensor mount consists of four holes that correspond to screw holes on the radar baseboard. The sensor is fastened with M2 screws and nuts. A small support structure is present on the left in order to keep the sensor levelled. The sensor mount creates a 20^o angle with the back plate to create the desired FoV when the prototype is mounted at a height of 2.3 meters.

Just below the radar mount is the mount for the Cam-PIR3.5. The existing sensor house is used to hold the circuit board and batteries (if used) in place. The back lid that protects the batteries has been removed and a mount identical to that of the back lid of the Cam-PIR is printed on the backboard. This means the device is easily snapped on to the back board.

Figure 5.3: *The back plate with mounts for the radar sensor on top, and the Cam-PIR3.5 below.*

5.4 Demonstration

In order to provide a better understanding of the functionality of the prototype, a mock burglary is performed to provide photos and radar data.

5.4.1 Set Up

The demonstration is carried out in one of Verisure's indoor test facilities as no suitable outdoor facilities are available. A central unit is installed to allow the Cam-PIR3.5 to wirelessly send the photos to a computer. A keypad is connected to the system to simplify arming and disarming of the alarm as well as to indicate when the alarm is triggered. The radar is connected to a computer to allow for real-time acquisition of data. The prototype set-up is pictured in figure 5.4.

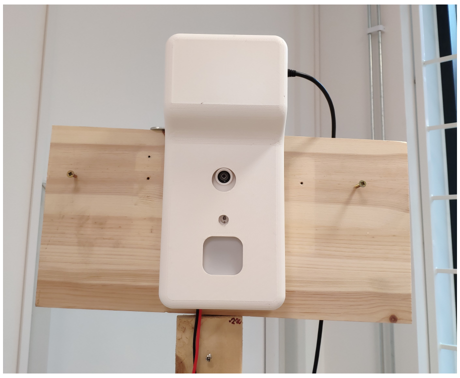


Figure 5.4: *The prototype.*

The test area is pictured in figure 5.5. The room is bigger than the eight by eight meters specified FoV, but the tester is instructed to move within a square of that size in front of the sensors. The prototype is mounted 2.3 m up in a corner of the room. Default settings are applied and the sensitivity level is 20/2000.

Figure 5.5: *The test area seen from the sensors perspective.*

5.4.2 Demonstration

The burglar enters from the left and moves across until he is detected. When the alarm sounds, he turns around and moves away from the sensors and through the open door in the background of figure 5.5. The event is over in ten seconds. Figure 5.6 shows the series of Cam-PIR3.5 photos.

(a) *First photo.*

(b) *Second photo.* ***(c)*** *Third photo.*

Figure 5.6: *Photos from Cam-PIR3.5 taken after the PIR-sensor has triggered.*

The radar is activated simultaneous to the capture of these photos. Figure 5.7 shows a plot of the motion detection and the signed velocity. The motion indication is one if motion is detected and zero otherwise. A positive velocity indicate motion towards the sensor and negative for movement away from it, in km/h.

Figure 5.7: A plot showing the motion indication in binary (yellow) and the signed velocity (green) in km/h over time.

The radar data in figure 5.7 indicate movement from the moment of activation (the yellow line is at one), even though no velocity or direction is resolved. This corresponds well to the actual scenario proven by the first photo (figure 5.6a), where the intruder is moving across the FoV which will not give speed or direction data. A velocity is then recognised, approximately negative four km/h (1.1 m/s), indicating a movement away from the sensor at a moderate walk speed. This corresponds to the burglar's movements in the second and third photo (figure 5.6b and 5.6c).

The velocity data from the radar is accurate when available, but motion is indicated both before and after the velocity measurements. Thus, the motion indication is the most accurate, but the velocity provides a better understanding of the motion and direction of the movement.

6. Discussion

In the discussion, the experiments and their outcome are analysed, followed by a comparison of the radar and PIR sensor. The applications are also discussed as well as the hardware choices made in this project.

6.1 Experiment Evaluation

At first glance, the Sense2GoL Pulse performs very well. It triggers fast, the range is at least the required 11.3 meters and it detects targets moving up to 6 m/s, despite the alleged limit of 3 m/s. The battery life time is estimated to be over five years for a radar-camera-PIR device, well over the desired three year demand. The radar is in many ways performing better than the PIR.

Although the radar performed well in the experiments, there are some issues that might become more prominent in a real garden environment. The challenges identified include the sensor's power consumption, detection of fast approaching targets and the sensitivity level threshold. Furthermore, there might be an issue with false alarms from wind affected plants and trees when the wind is more powerful than during the *Outdoor Test* (section 4.2.7). These problems will be discussed further below.

6.1.1 Approaching Target

In the *Velocity* test (section 4.2.4), the sensor had obvious problems with a person moving straight towards the sensor and was slow to indicate motion. This is troubling; however, Verisure only requires motion detection of objects moving slower than 2 m/s. This effect is not at all as prominent at lower speeds (<3m/s). Though this is now a known issue, there is no need to take any countermeasures. The tester was detected, and that is good enough.

6.1.2 Sensitivity Level Threshold

For all the tests carried out in the indoor test facility, the sensitivity level was set to 4/2000. These tests produced good results, with fast and accurate motion detection, except in a few cases. When the same threshold was applied in the *Outdoor Test* (section 4.2.7), the radar sensor triggered a lot, only the slightest plant movement caused it to indicate motion. To avoid these false triggers from plants blowing in the wind and similar disturbances, a more suitable threshold turned out to be about somewhere between 10 and 20/2000.

Looking at the *Sensitivity Level* walk tests (section 4.2.2) at sensitivity threshold 20/2000 (figure 4.7b), the detection rate and accuracy is significantly worse than the one at 4/2000 (figure 4.6a in section 4.2.1). The search of an optimal threshold could be further investigated, but from the experiments conducted in this report, it seems likely that the optimal value is somewhere between 10/2000 and 20/2000.

Even though finding an appropriate threshold is valuable, there might be other ways to solve this problem. Making the digital signal processor more advanced and using more parameters to determine whether to trigger the alarm or not may help with false alarms. There are reports indicating that artificial intelligence and machine learning could be used to successfully distinguish human targets [15]. Also other analysis methods of the radar signature may allow a lower threshold while still maintaining a fast and accurate detection. This is an important aspect of the radar's adequacy as an intrusion detection alarm, and should be further investigated.

6.1.3 Battery Lifespan

From the measurements performed in the *Battery Lifespan Estimation* (section 4.2.9), it was made clear that the energy needed to power the radar sensor is relatively small compared to the energy needed to power the camera and illumination system of the PIR product. This means the radar will not have any major effect on the power consumption if it is to be used as a second opinion alongside the camera.

If the radar was to replace the PIR completely, it would decrease the battery lifespan drastically. The *Output Power and Performance* experiment (section 4.2.8) shows that it is possible to decrease the power consumption by adjusting the frame rate. More extensive testing with the best low power state (state 2) should be performed to verify that it is good option. However, with an average current of 0.7mA that the low power state consumes, the battery lifespan would be approximately a year and a half. Although having the radar as the primary sensor would be preferable, it is not a realistic solution if the system is battery powered.

6.1.4 Power On Latency

The initial idea was to conduct an experiment to verify that the latency from power on to first measurement is in fact one second, as claimed by Infineon. However, this was not feasible with the available equipment at Verisure. Instead, a simulation was provided by Infineon to provide some verification. Due to an NDA, the simulation plot and the simulated circuit cannot be shared in this report.

The latency has been a concern ever since the decision to go forward with the Sense2GoL Pulse was made. Nevertheless the sensor passed the test described in *Use Case* (section 4.2.5); the target was detected before leaving the FoV. Unsurprisingly, the tester got further before detection in the tests with delay than in the tests without.

The experiment shows that the latency might not actually be a problem. If it turns out to be an issue after further testing, it will be possible to speed up the boot-up time. This comes to the cost of a decreased target speed span [32]. In the *Velocity* test (section 4.2.4); however, the speed of the target made little difference to the detectability when the target moved across the FoV from either side or from behind the sensor. 6 m/s speeds were as easily detected as the moderate 1 m/s, even though the alleged speed limit is 3 m/s.

6.2 PIR and Radar Comparison

In the EN-tests described in (section 4.2.1) where the Infineon radar was tested according to PIR sensor standards, the goal was to distinguish the differences in performance and to highlight the advantages of radar over PIR. There are many, such as a better robustness for weather, the ability to see through some materials and information on whether the target is approaching or departing from the sensor.

Comparing the radar results in figure 4.6 with the Cam-PIR3.5 results, the radar performance is overall better. The detection rate is higher, and the target is spotted very close to the test area borders. The radar results show no indication of a too narrow FoV, which was one of the concerns beforehand. From this, it can be concluded that the radar sensor has the potential of outperforming the PIR.

In the results from the crawl and belly crawl tests however, it was clear that the radar struggled more to detect the target at greater distances or when the silhouette of the tester was different. A possible reason to this problem could be the angle that the sensor was mounted with. The angle was chosen based on some simple tests conducted before the creation of the sensor mount, but no thorough optimisation of the radar tilt angle took place. Conducting further tests may improve the overall performance of radar as the FoV horizontally, but especially vertically, would be optimised.

Although the radar has numerous advantageous characteristics, the PIR sensor is still superior in some aspects. The fact that the PIR is considerably more power efficient has been mentioned previously in this report. With Verisure battery set-up, this is the greatest advantage of the PIR and the most obvious disadvantage of the radar sensor. The PIR sensor is based on relatively simple technology making it cheap. The in-house knowledge of PIR sensors at Verisure is also greater than the knowledge of radar.

6.3 Use Case and Applications

Because of the radar's high power consumption, it was argued in section 3.2 that the only reasonable way of implementing the radar is together with a PIR, with the PIR waking the radar if movement is detected. However, there are issues that come with this set-up. The initial intention of investigating a radar solution was to avoid

PIR-caused false alarms, but also to trigger on events that usually go unnoticed by the PIR. As described in section 2.5, there is proof that a person can trick the PIR with a bed sheet. By using the PIR as the first filter, these events will not trigger the radar. They will remain undetected, even though it may be likely that the radar would have triggered given the opportunity.

One way to try to get around this problem is to lower the threshold of the PIR, and allow the radar to provide a second opinion more often. This may work in some cases, but there is still a chance that it is not enough. However, having the radar in an off state does allow for the use of a more complex radar. When used as a secondary sensor, a radar's power consumption will be relatively small compared to the PIR's (see calculations in section 4.2.9), as it is in off mode most of the time. This means a FMCW radar could be used to resolve distance, separate multiple target and provide more accurate data. From this perspective, the choice of the Sense2GoL Pulse is not ideal, as it is too power consuming to be used as a primary sensor but still lacks the features of an FMCW sensor.

Using the radar as the primary sensor would be preferable, as it would solve the problems of the PIR completely. This use case was discarded due to the high power consumption that was not feasible with the goal of a battery life of more than three years. The reason Verisure requires this is because every time the batteries need to be replaced, a technician is sent out to the homeowner to change the batteries. This is obviously expensive, thus a long battery lifetime is desirable. If users could change the batteries themselves, it is possible that a battery lifetime of one year and a half, which was the estimated lifetime of the low power settings on the Sense2GoL Pulse, could be acceptable. Another possible solution that could improve battery lifetime is the use of solar panels on the sensor house, as it is mounted outside. Solutions like these could change the outlook for the radar as a single or primary sensor.

6.3.1 Outdoor Use

In the *Outdoor Test* (section 4.2.7), the Sense2GoL Pulse was tested outdoors in very mild weather. In order to fully investigate how it behaves in an outdoor environment, further testing in heavy rain, snow, fog and high winds is necessary.

To further expand the knowledge of potential false triggers outdoors, the DSP needs further development. In a garden, the wild animals can vary from mice to deer. How these movements can be filtered out must be investigated in order to build an animal immune sensor.

Considering the use of a radar as a second opinion will likely increase the certainty of the cause of the PIR sensor's triggers. The potential false triggers for the PIR in an outdoor environment have not been investigated at all in this report. This is a very important factor that has to be investigated and tested thoroughly as the performance of the whole device is dependent on the PIR sensor performance.

6.3.2 Prototype and Radar Implementation

The prototype that was built shows that the integration between a Cam-PIR3.5 and the Infineon Sense2GoL Pulse is relatively simple. The prototype is big in size because of the Infineon baseboard and the fact the the whole Cam-PIR3.5, with casing and all, was built in. By using a different microcontroller board for the radar sensor and optimising the internal placement of the components, a product with the same functionality could be a lot smaller and leaner.

6.3.3 Privacy

The one aspect of the radar sensor that is rather different from the other factors considered in this report is related to privacy and integrity. Radar, just like PIR, can monitor a room without identifying the person, unlike a camera. In today's society, some people may be hesitant to installing a camera in their home in fear of being monitored without their knowledge. Using a radar instead may be more appealing.

Replacing the camera of the Cam-PIR3.5 with a radar could give a just as good confirmation of an intrusion, although there is one major difference. From an evidence and crime solving point of view, a camera photo will always be superior to a radar confirmation or even a radar image. It will not be possible to replace a camera with a radar and achieve the same identification possibilities.

6.4 Radar Properties

6.4.1 Frequency and Modulation

Whether the radar could resolve the distance to the target or not was disregarded when the choice between the Infineon fixed frequency radar and TI' frequency modulated was made. This was due to the main goal of being able to detect a moving target in the FoV, thus the distance to the target was not seen as a necessity.

Although the distance was not considered in this study, there may be some benefits of collecting information about this as well. Information about the distance to the target could possibly give the alarm system the ability to filter out potential false triggers, such as people passing by on the pavement, outside of the desired garden monitoring area.

The Infineon sensor can be used for range detection, but then requires an external phase-locked loop that will add cost and increase power consumption. It may be worth considering to use an FMCW 24 GHz radar to be able to resolve the distance. This is especially important if the radar will be used as a secondary sensor, since the power consumption is relatively low compared to the camera (as seen in the *Battery Lifespan Estimation* experiment, section 4.2.9).

7. Conclusion

The conclusion will include a summary of the findings in this report as well as a description of how this project can be continued under "Future Work".

The radar concept that has been investigated in this master thesis has showed a lot of potential. The usage of radar in home alarm systems is not only possible, but also in most aspects advantageous over a PIR sensor. In an indoor environment, the implementation is straight forward; an outdoor application requires more testing and evaluation.

The Infineon Sense2GoL Pulse fulfils all of Verisure's demands regarding range, detectable speed of target, FoV and operating temperature. The battery lifetime has been the main concern and is the greatest flaw compared to a PIR sensor. By implementing the radar sensor as a secondary sensor to the PIR and keeping the radar in an off-state until the PIR triggers and wakes it up, the battery life time will be maintained at an acceptable level. However, this causes the device to lose some of the benefits of radar and does not eliminate all issues with PIR, which was initially intended.

7.1 Future Work

In this report, the main focus has been radar hardware and functionality, rather than signal processing. A digital signal processor that can filter out wind-caused movements in trees or bushes and wild animals as well as improve human movement identification is essential to secure an accurate radar performance. To what extent this is possible will determine how to move forward with the objective of implementing radar in home alarm systems.

A more extensive evaluation on whether to have the radar as a primary sensor or secondary sensor is the better option should be performed. Implementing radar as a primary sensor would result in limited performance in order to reach a realistic power consumption. Using the radar as a secondary sensor enables it to have more advanced features, such as utilising frequency modulation to measure distance to the target and to resolve multiple targets.

As the power consumption is the main problem with all radar sensors today, considering changing the batteries more frequently or using more batteries are important aspects to consider. As mentioned in *Discussion*, considering alternative ways to solve the power consumption problem such as the use of solar power or consumer changeable battery solutions could be highly beneficial.

Finally, staying up to date with new products on the market, especially improvements that decrease power consumption, will be beneficial to Verisure. As the technology within the field is developing and improving rapidly, it is possible that there will soon be a solution to the problems of today.

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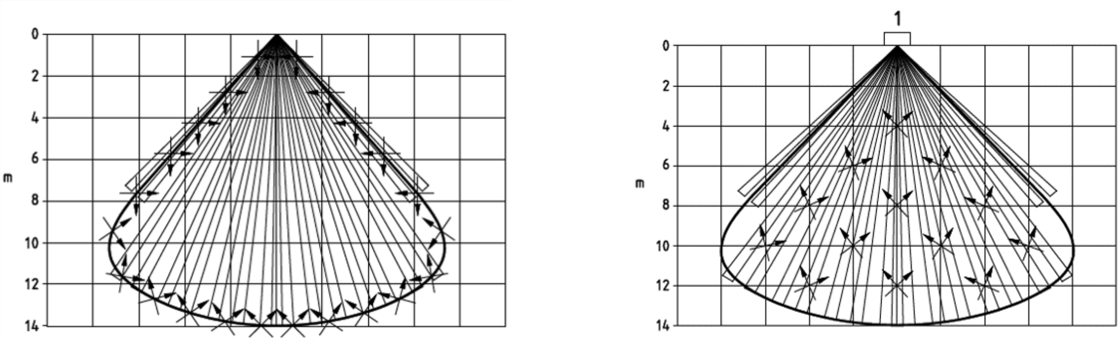
Appendices

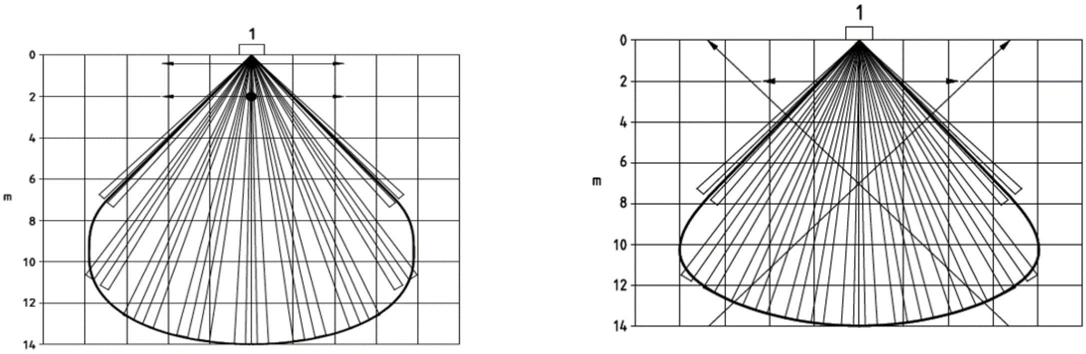
A. EN 50131-2-2 Test

A.1 Walk Patterns



(a) *Detection across the boundary.*

(b) *Detection within the boundary.*

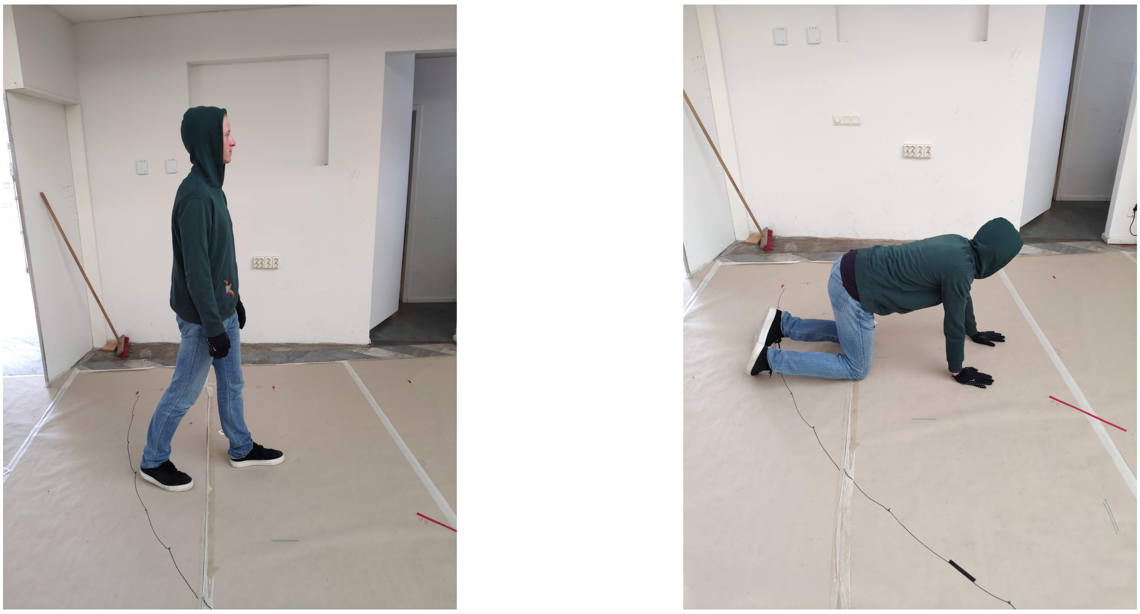


(c) *Close-in detection performance*

(d) *Detection at high velocity.*

Figure A.1: *Walk tests. Figure from [30].*

A.2 Movement Demonstration



(a) *Walking.*

(b) *Crawling.*

(c) *Belly crawling.*

Figure A.2: *Movement demonstration.*

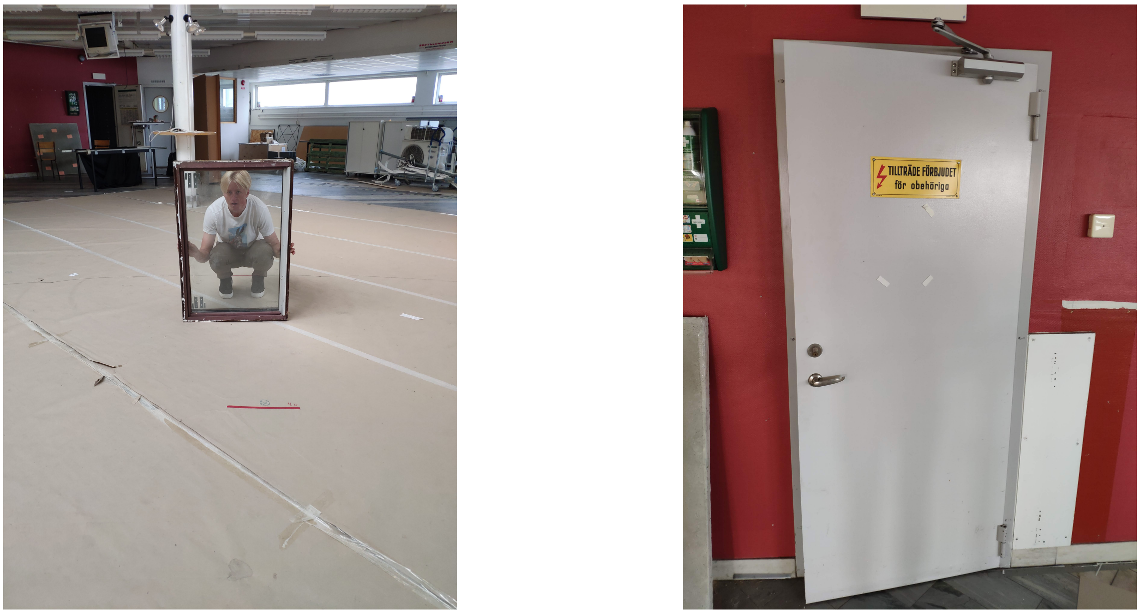
B. Penetrative Ability Test

(a) Nothing.

(b) Cardboard.

(c) Plant.

(d) Wood.



(e) Glass.

(f) Metal.

Figure B.1: *Material and obstacles for the penetrative ability test.*