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Comparison of Millimeter Wave Radar Sensors

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Abstract

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Millimeter wave (mmWave) radar employs electromagnetic waves within the millimeter-wave band, ranging frequencies from 30 to 300 GHz. It offers numerous benefits compared to alternative radar types, such as enhanced resolution, deep penetration capabilities, and minimal interference. These advantages render mmWave radar highly suitable for diverse applications spanning automotive, security, and manufacturing sectors.

The purpose of this thesis is to compare 24 GHz and 60 GHz mmWave radar sensors. The thesis begins with a literature review of mmWave radar, including its history, applications, and the 24 GHz and 60 GHz bands. The thesis then describes the design of the 24 GHz and 60 GHz mmWave radar systems. The work concludes with a presentation of the experimental results for the two systems, including the range performance, resolution performance, and penetration performance.
As a source material the data sheet of the two sensors was used.

As result it appears that each band has its own advantages and disadvantages. 24 GHz radar has better penetration and range than 60 GHz radar, but it has lower resolution. 60 GHz radar has higher resolution than 24 GHz radar, but it has shorter range and worse penetration.

Contents

List of Abbreviations

CW: Continuous Wave

FMCW: Frequency Modulated Continuous Wave

LiDAR: Light Detection and Ranging

mmWave: Millimeter wave

NDS: Near Distance Sensor

1 Introduction

Millimeter wave (mmWave) radar is a type of radar that uses electromagnetic waves in the millimeter -wave band, which has frequencies from 30 to 300 GHz. mmWave radar has several advantages over other types of radar, including high resolution, good penetration, and low interference. These advantages make mmWave radar well-suited for a variety of applications, including automotive, security, and manufacturing.

The mmWave radar operate in the following way:

- Transmitter: the transmitter in a mmWave radar system emits a beam of millimeter waves.
- Receiver: the receiver in the system detects the reflected millimeter waves from objects in the environment.
- Signal processing: the reflected millimeter waves are processed to determine the range, velocity, and angle of the objects.

Distance detection in mmWave radar depends on a balance between the strength of the signal it sends out (transmitter power) and its ability to pick up weak echoes (receiver sensitivity). Stronger signals and more sensitive receivers can reach farther.

To determine an object's speed, mmWave radar works like bouncing a ball off a wall. It measures the time it takes for its signal to bounce off an object and return. By comparing this time difference, it can calculate how fast the object is moving.

Finally, mmWave radar can determine the location of an object by analysing the direction of the bouncing signal (reflected millimeter waves). Imagine using the echo to pinpoint where the wall is based on where the ball bounced back. mmWave radar is a powerful tool that can be used to detect and track objects in a variety of environments. As the cost of mmWave radar systems continues to decrease, we can expect to see even more widespread adoption of this technology in the future.

The two most common mmWave radar bands are 24 GHz and 60 GHz. Each band has its own advantages and disadvantages. 24 GHz radar has better penetration and range than 60 GHz radar, but it has lower resolution. 60 GHz radar has higher resolution than 24 GHz radar, but it has shorter range and worse penetration.
This thesis presents a comparison of 24 GHz and 60 GHz mmWave radar sensors. The thesis begins with a literature review of mmWave radar, including its history, applications, and the 24 GHz and 60 GHz bands. The thesis then describes the design of the 24 GHz and 60 GHz mmWave radar systems. The thesis concludes with a presentation of the experimental results for the two systems, including the range performance, resolution performance, and penetration performance.

The purpose of the work was to provide a comprehensive comparison of 24 GHz and 60 GHz mmWave radar sensors, to design and implement 24 GHz and 60 GHz mmWave radar systems, and to evaluate the performance of the 24 GHz and 60 GHz mmWave radar systems in terms of range, resolution, and penetration.

The thesis will provide insights into the advantages and disadvantages of 24 GHz and 60 GHz mmWave radar sensors. The thesis will also provide data on the performance of these sensors in real-world conditions.

2 Literature Review

2.1 History of millimeter wave radar

Millimeter wave (mmWave) radar was first developed in the 1940s for military applications. However, it was not until the 1990s that mmWave radar began to be used for commercial applications. This was due to the development of new technologies, such as solid-state transistors and integrated circuits, which made mmWave radar systems more affordable and practical. [5,1.]

2.2 Applications of millimeter wave radar

mmWave radar has a wide range of applications, including:

- Automotive: mmWave radar is used in autonomous vehicles to detect and track other vehicles, pedestrians, and objects on the road.
- Security: mmWave radar is used in security systems to detect and track intruders.
- Manufacturing: mmWave radar is used in manufacturing to inspect products for defects and to measure the distance between objects.
- Medical: mmWave radar is used in medical devices to image internal organs and tissues.
- Telecommunications: mmWave radar is used in 5G and beyond 5G networks to provide high-speed data transmission.

2.3 24 GHz millimeter wave radar

24 GHz mmWave radar is the most common type of mmWave radar. Its versatility extends across various applications, including automotive, security, and manufacturing. 24 GHz mmWave radar has several advantages, including:

- Good penetration: 24 GHz mmWave radar can penetrate fog, rain, and snow, which makes it well-suited for outdoor applications in all weather conditions.
- Long range: 24 GHz mmWave radar has a longer range than 60 GHz mmWave radar.
- Lower cost: 24 GHz mmWave radar systems are less expensive than 60 GHz mmWave radar systems.

However, 24 GHz mmWave radar also has some disadvantages, including:

- Lower resolution: 24 GHz mmWave radar has lower resolution than 60 GHz mmWave radar.

- More susceptible to interference: 24 GHz mmWave radar is more susceptible to interference from other electromagnetic waves, such as those from radio and TV broadcasts.

  The 24GHz mmWave sensor MR24FDB1 by seeed Studio was selected for this thesis work, which is ideal for fall detection, smart home, and health care.

Features of the 24 GHz mmWave radar:
This system uses reliable Infineon millimeter wave (mmWave) radar technology to detect people in a self-adapting environment. It operates at a safe frequency of 24 GHz and utilizes standard algorithms to distinguish between occupied and unoccupied states, even identifying human activities. This privacy-preserving, wireless system can be worn by a single user and effectively covers an area of up to 20 square meters. It detects falls, both fast and slow, along with periods of inactivity that may be a cause for concern.

- Reliable and safe technology: Uses mmWave radar from a reputable brand (Infineon) and operates at a safe frequency (24 GHz).
- Multi-purpose: Detects presence, distinguishes activities, and identifies falls.
- Adaptable: Works in various environments.
- Privacy-focused and convenient: Wireless and wearable for single-user applications.
- Effective range: Covers up to 20 square meters.
- Accurate: Achieves high accuracy (>95%) with minimal interference from non-living objects.
- Detailed detection: Senses even slight movements (micromotion) and detects people up to 5 meters away.
  [2,1.]

2.4 60 GHz Millimeter Wave Radar

60 GHz millimeter-wave (mmWave) radar stands out as a newer technology within the mmWave radar family. It boasts two key advantages:

- Exceptional Resolution: Compared to other mmWave radars, the 60 GHz version offers superior resolution. This makes it particularly valuable in applications like medical imaging and security, where capturing fine details is crucial.
- Minimized Interference: 60 GHz mmWave radar experiences significantly lower interference compared to other frequencies. This is advantageous in situations where external signals can disrupt operation, such as telecommunications environments.

However, 60 GHz mmWave radar also has some disadvantages, including:

- Poor penetration: 60 GHz mmWave radar cannot penetrate fog, rain, or snow, which limits its use in outdoor applications.
- Shorter range: 60 GHz mmWave radar has a shorter range than 24 GHz mmWave radar.
- Higher cost: 60 GHz mmWave radar systems are more expensive than 24 GHz mmWave radar systems.

The 60GHz mmWave Sensor MR60BHA1 by seeed studio was selected for this thesis work, which is ideal for smart home, health care, breathing/ heartbeat rate detection, medical assistants.

Features of the 60GHz mmWave Sensor:

- Radar-based fall detection using FMCW continuous wave signals.
- Provides real-time feedback on both respiration and cardiac activity, adjusting automatically to environmental fluctuations.
- Provides surveillance capabilities without identification using FMCW monitoring technology.
- Safe operational state: emitting a power of 6 dBm of harmless energy.
- Extremely stable and unaffected by changes in light, airflow, temperature, humidity, noise, or other external factors.
- Excellent measurement accuracy, with breathing accuracy reaching 90% and heartbeat accuracy reaching 85%.

- Flexible hardware design supports secondary development for various applications.

  [4,1.]

3 Theory and Principles

3.1 Radar fundamentals

3.1.1 Radar operating principles

Radar, short for "Radio Detection and Ranging," is a remote sensing technology that utilizes electromagnetic waves for detecting and pinpointing objects in the vicinity. This segment will offer insights into the core principles governing radar functionality.

3.1.2 Transmission and reception

Radar systems operate by transmitting high-frequency electromagnetic waves, typically in the microwave or millimeter -wave spectrum, toward the target area. These waves propagate through space until they encounter an object, at which point they are partially reflected back toward the radar antenna. The radar system's receiver detects the return signals, allowing for the calculation of various object parameters, including distance, speed, and direction.

3.1.3 Echo signal processing

Upon reception of reflected signals, radar systems utilize signal processing methods to extract crucial data. This involves measuring the time delay between signal transmission and reception (time-of-flight), which yields the target's distance (range). Additionally, Doppler shifts in the received signal are analyzed to ascertain the target's radial velocity.

3.1.4 Types of radar systems

Different radar systems serve various purposes, and their operating principles may vary accordingly. In this section, a common types of radar systems are explained, including:

- Pulse radar: pulse radar systems emit short pulses of electromagnetic waves and measure the time it takes for the echo to return. These systems are widely used in applications such as weather radar and air traffic control.
- Continuous Wave (CW) radar: CW radar transmits an uninterrupted wave and gauges the frequency shift in the received signal to ascertain the velocity of the target. While adept at speed measurement, this type lacks range resolution.
- Frequency-Modulated Continuous Wave (FMCW) radar: FMCW radar emits a continuous wave with a frequency that linearly changes over time. By examining the frequency variance between the transmitted and received signals, FMCW radar furnishes both range and velocity data.
- Doppler radar: doppler radar specializes in detecting the motion of objects, making it useful in applications such as speed guns and automotive collision avoidance systems.

3.2 Electromagnetic waves at 24GHz and 60GHz

3.2.1 Millimeter -wave spectrum

The millimeter -wave (mm-wave) spectrum encompasses frequencies from 30GHz to 300GHz, and it has gained significant attention for radar and communication applications. this section will explore the properties of electromagnetic waves in the 24GHz and 60GHz bands, which are of particular interest for this thesis work.

3.2.2 Wavelength and propagation

Understanding the wavelength characteristics of mm-wave frequencies is crucial for radar design and propagation analysis. the shorter wavelengths at 60GHz offer higher resolution but may suffer from increased atmospheric absorption compared to the longer wavelengths at 24GHz.

3.2.3 Regulatory considerations

This regulation, labelled as Radio Frequency Regulation 4 AD /2023M, outlines rules for using the radio frequency spectrum from 100 Hz to 400 GHz. It specifies that radio transmitters operating on these frequencies must comply to guidelines regarding transmitting and receiving frequencies, channel spacing, transmission bandwidth, duplex separation, transmitted power, and other radio-related characteristics. Additionally, electrical equipment, excluding radio equipment (ISM equipment), designed for generating radio frequency energy in scientific, industrial, medical, or similar contexts, can only be used on these radio frequencies following the conditions set in this regulation.

The main goal of this regulation is to ensure fair, efficient, appropriate, and interference-free use of radio frequencies. The document includes a Frequency Allocation Table in the annex, which outlines the allocation of radio frequencies, frequency bands, and sub-bands for various purposes. This table also covers radio interface requirements and specifies frequency bands for ISM equipment, along with the terms of use outlined in Section 1 of the regulation. [6]

3.3 Radar signal processing techniques

3.3.1 Signal processing basics

Signal processing plays a vital role in extracting meaningful information from radar data. There are fundamental signal processing techniques employed in radar systems, including:

- Pulse compression: pulse compression techniques, such as matched filtering, enhance range resolution and reduce the effects of noise.

- Clutter mitigation: radar systems must distinguish between actual targets and unwanted clutter, such as ground reflections and environmental interference.

- Target detection and tracking: signal processing algorithms for target detection and tracking, including Kalman filtering and adaptive beamforming.

3.3.2 Data fusion and multi-sensor integration

In modern radar systems, data fusion and integration with other sensors, such as cameras and LiDAR, are common practices to improve situational awareness and target identification.

3.4 Key Parameters for radar performance

Radar performance is influenced by a range of parameters that affect its sensitivity, accuracy, and reliability. The essential radar performance parameters, including:

- Range resolution: How closely radar can distinguish between two targets in the radial direction.
- Angular resolution: The capacity to differentiate between two targets in either the azimuthal or elevation direction.
- Doppler resolution: The capacity of the radar to distinguish between targets with varying velocities.
- Sensitivity and noise figure: Measures of the radar's ability to detect weak signals in the presence of noise.
- Interference susceptibility: Considerations related to electromagnetic interference and jamming in radar systems.

This chapter lays the theoretical foundation for understanding the operation and principles of radar technology, with a specific focus on the 24GHz and 60GHz mm-wave frequencies.

4 System Design

4.1 Hardware design of the 24 GHz millimeter wave radar system

The objective of the system design is to detect when the environment is being utilized by someone in a static position., or someone moving in the environment and to turn the LED lights accordingly.

The hardware system design for the 24 GHz mmWave Radar includes:

- 24 GHz mmWave radar sensor

- Seeed XIAO BLE nRF52840
- 2 LED (Red and Green)
- 2 x 220Ω resistors.

The seeed Studio XIAO nRF52840 Sense is a small, low-power computer board that can be used to build individual IoT and wearable devices. It has Bluetooth, NFC, and a 6-axis IMU sensor built in.

The XIAO nRF52840 Sense can be programmed with Arduino, C++, CircuitPython, or Zephyr RTOS. It also works with a wide range of expansion boards from seeed Studio, so more features can be added to projects.

Some examples of different systems that can be built with the XIAO nRF52840 Sense include smart home devices, fitness trackers, industrial sensors, environment monitors, game controllers.

4.2 24GHz mmWave radar system

The 24GHz mmWave radar is connected to the seeed XIAO BLE, and from the XIAO BLE connected to two resistors and LED’s as shown in figure 1 bellow.

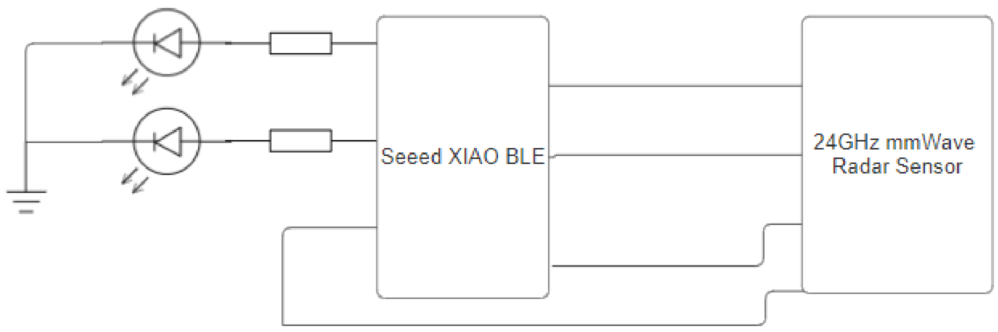

Figure 1. A Block diagram of the 24GHz mmWave radar system

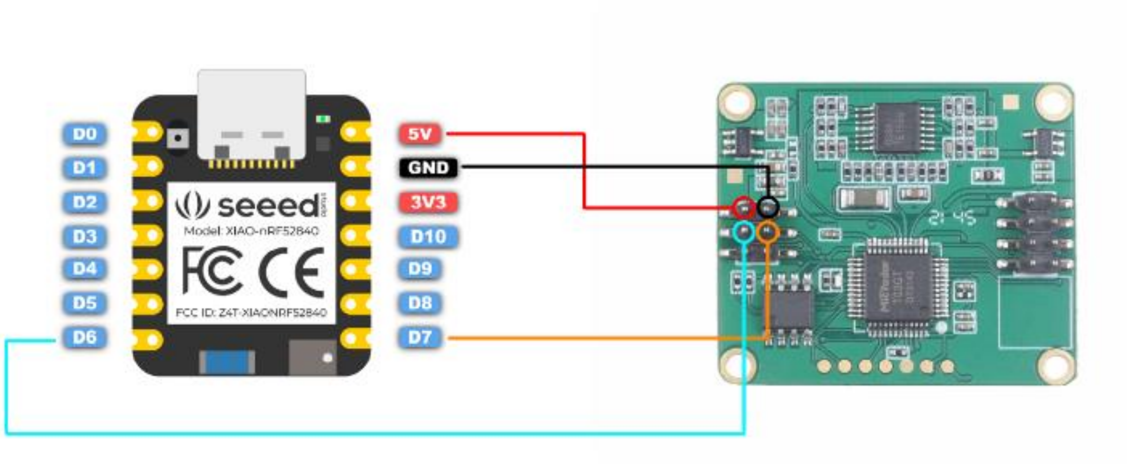

Figure 2. A wiring diagram of the 24GHz mmWave radar and the seeed XIAO BLE nRF52840. [2,1].

4.3 Software design of the 24GHz system

Arduino IDE software is being installed, programming using C++, this sensor will be used with a custom C++ script, which will be described below in listing 1.

```
#include <falldetectionradar.h>

FallDetectionRadar radar;

void setup()
{
  radar.SerialInit();
  Serial.begin(9600);
  delay(1000);
  Serial.println("Readly");
  pinMode(D0, OUTPUT);
  pinMode(D1, OUTPUT);
}

void loop()
{
 radar.recvRadarBytes();
 if (radar.newData == true) {
    byte dataMsg[radar.dataLen+1] = {0x00};
    dataMsg[0] = 0x55;

    for (byte n = 0; n < radar.dataLen; n++)dataMsg[n+1] = radar.Msg[n];
    radar.newData = false;

    radar.ShowData(dataMsg);
    radar.Bodysign_judgment(dataMsg, 1, 15);

    /* if (dataMsg[7] == true && dataMsg[6] == false) {
      digitalWrite(D0, HIGH);
      digitalWrite(D1, HIGH);
    }
```

```
    else if (dataMsg[7] == false && dataMsg[6] == false) {
      digitalWrite(D0, HIGH);
      digitalWrite(D1, LOW);
    }
    else if (dataMsg[7] == false && dataMsg[6] == true) {
      digitalWrite(D0, LOW);
      digitalWrite(D1, LOW);
    } */

    typedef union
  {
    unsigned char Byte[4];
    float Float;
  } Float_Byte;
    if(dataMsg[3] == ACTIVE_REPORT){
     if(dataMsg[5] == BODYSIGN){
       Float_Byte fb;
       fb.Byte[0] = dataMsg[6];
       fb.Byte[1] = dataMsg[7];
       fb.Byte[2] = dataMsg[8];
       fb.Byte[3] = dataMsg[9];
       Serial.println(fb.Float);
       if(fb.Float >= 1 && fb.Float < 15){
         digitalWrite(D0, HIGH);
         digitalWrite(D1, LOW);
       }
       else if(fb.Float < 1){
         digitalWrite(D0, LOW);
         digitalWrite(D1, LOW);
       }
       else if(fb.Float >= 15){
         digitalWrite(D0, HIGH);
         digitalWrite(D1, HIGH);
       }
     }
    }
  }
}
```

Listing 1. The code is a fall detection radar system using the falldetectionradar.h library. The library provides functions for initializing the radar, receiving, and processing radar data, and detecting falls.

The radar is initialized, and the serial port is configured to 9600 baud. A delay of 1 second is added to allow the radar to start up.

The loop() function is where the fall detection system runs. The first step is to call the recvRadarBytes() function to receive radar data and initiate processing. If the newData flag is set to true., it means that a complete set of radar data frames has been received.

The received data frames are then printed to the serial port by calling the ShowData() function. Then, using the sign parameters, the Bodysign_judgment() function is invoked to identify the human movement.

The code then checks the value of the dataMsg[7] and dataMsg[6] parameters. If dataMsg[7] is true and dataMsg[6] is false, then the BODYSIGN flag is set. This means that a human body has been detected.

If the BODYSIGN flag is set, then the code converts the body sign value from bytes to a float using the Float_Byte union. The code then checks the value of the body sign float. If the value is between 1 and 15, then the code sets the D0 pin to HIGH and the D1 pin to LOW. Someone is currently present in the environment, remaining stationary.

If the BODYSIGN float is less than 1, then the code sets the D0 and D1 pins to LOW. This indicates no one is in the environment. If the body sign float is greater than 35, then the code sets the D0 and D1 pins to HIGH. This indicates that there is someone moving in the environment.

After uploading the code, the serial monitor will display as shown in figure 3.

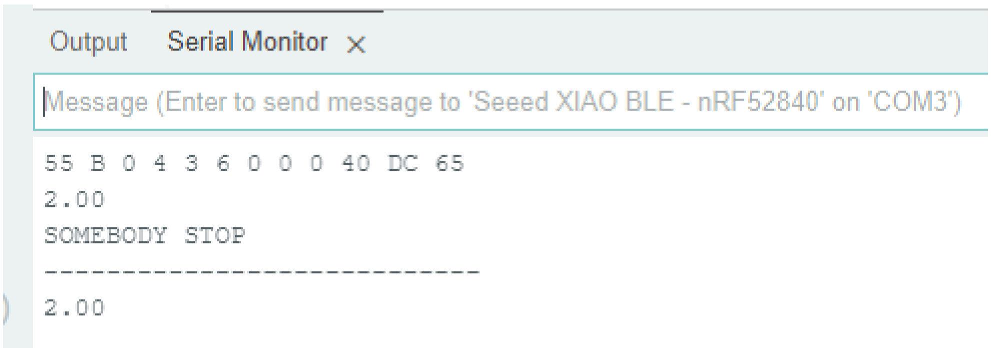

Figure 3. Serial monitor

Definition and description of the frame structure:

Starting Code	Length of data		Function codes	Address code 1	Address code 2	Data	Check Code	
0X55	Lenth_L	Lenth_H	Command	Address_1	Address_2	Data	Crc16_L	Crc16_H
1 Byte	1 Byte	1 Byte	1 Byte	1 Byte	1 Byte	n Byte	1 Byte	1 Byte

Figure 4. Frame structure definition, as indicated in the user manual [3,9].

Description of the frame structure as seen in figure 4:

a. Initial code: 1Byte, set to0X55.
b. Data length: 2 bytes, with the low byte preceding the high byte. The length is calculated as adding the data length, function code, address code 1, address code 2, data, and checksum.
c. Function code: 1 byte.
   Read command: 0X01.
   Write command: 0X02.
   Passive report command: 0X03.
   Active report command: 0X04.
d. Address code:
e. Address code indicates the function category.
   Address code 2 indicates the specific function.
   Refer to the address assignment and data information description for further details.
   Data: n Byte.
   Checksum: 2 bytes, with the low byte preceding the high byte.
   [2].

4.4 Hardware design of the 60 GHz millimeter wave radar system

The MR60BHA1 radar sensor is highly precise in measuring both breathing rate and heart rate., even in noisy places. It is used in many different products, such as wearable devices, medical equipment, and industrial sensors.
The objective of the system design is to measure breathing rate and heart rate and to turn the LED lights accordingly.

The hardware system design for the 60 GHz mmWave Radar includes a 60 GHz mmWave radar sensor, Seeed XIAO BLE nRF52840, 2 LED (Red and Green) and a 2 x 220Ω resistors. As shown in figure 5 below.

The MR60BHA1 60GHz radar module stands out as a versatile and accurate sensor for measuring breathing and heart rate. This reliable tool finds applications across smart homes, healthcare, and even industrial settings due to its high stability, ensuring consistent and accurate readings, and its highly flexible hardware design that adapts to diverse needs.

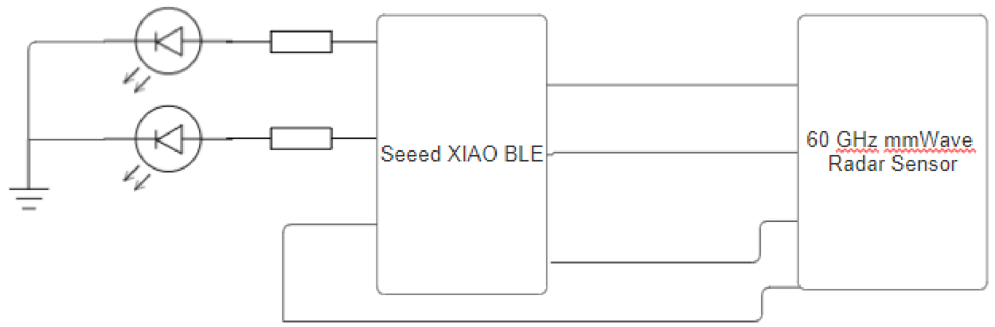

Figure 5. Block diagram of the 60GHz mmWave radar system.

The wiring of the 60GHz mmWave radar and the seeed XIAO BLE is as shown below in figure 6.

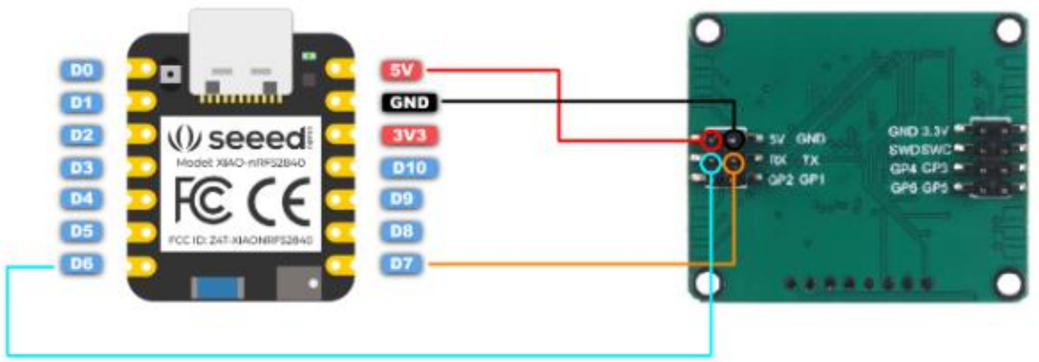

Figure 6. A wiring diagram of the 60GHz mmWave radar and the Seeed XIAO BLE nRF52840. [4,1].

Table 1. Wiring instructions

Seeed Studio XIAO	Sensor 60GHz
5V	5V
GND	GND
RX	D6
TX	D7

The wiring of the seeed studio and the sensor are conducted according to the instructions as shown in table 1.

4.5 Software design of the 60GHz system

Arduino IDE software is being installed, programming using C++, this sensor will be used with a custom C++ script, which will be described below in listing 2.

```
#include "Arduino.h"
#include <60ghzbreathheart.h>
BreathHeart_60GHz radar = BreathHeart_60GHz(&Serial1);
void setup() {
  Serial.begin(115200);
  Serial1.begin(115200);
  pinMode(D0, OUTPUT);
  pinMode(D1, OUTPUT);
  while(!Serial);
  Serial.println("Ready");
  radar.ModeSelect_fuc(1);
}
void loop()
{
  radar.Breath_Heart();
  if(radar.sensor_report != 0x00){
    switch(radar.sensor_report){
      case HEARTRATEVAL:
        Serial.print("Sensor monitored the current heart rate value is: ");
        Serial.println(radar.heart_rate, DEC);
        Serial.println("----------------------------");
```

```
    if (radar.heart_rate > 70) {
      digitalWrite(D0, HIGH);
      digitalWrite(D1, HIGH);
    }
    else if (radar.heart_rate <= 70 && radar.heart_rate > 50) {
      digitalWrite(D0, HIGH);
      digitalWrite(D1, LOW);
    }
    else {
      digitalWrite(D0, LOW);
      digitalWrite(D1, LOW);
    }
    break;
  case HEARTRATEWAVE:
    Serial.print("The heart rate waveform(Sine wave) -- point 1: ");
    Serial.print(radar.heart_point_1);
    Serial.print(", point 2 : ");
    Serial.print(radar.heart_point_2);
    Serial.print(", point 3 : ");
    Serial.print(radar.heart_point_3);
    Serial.print(", point 4 : ");
    Serial.print(radar.heart_point_4);
    Serial.print(", point 5 : ");
    Serial.println(radar.heart_point_5);
    Serial.println("----------------------------");
    break;
  case BREATHNOR:
    Serial.println("Sensor detects current breath rate is normal.");
    Serial.println("----------------------------");
    break;
  case BREATHRAPID:
    Serial.println("Sensor detects current breath rate is too fast.");
    Serial.println("----------------------------");
    break;
  case BREATHSLOW:
    Serial.println("Sensor detects current breath rate is too slow.");
    Serial.println("----------------------------");
    break;
  case BREATHNONE:
    Serial.println("There is no breathing information yet, please wait...");
    Serial.println("----------------------------");
    break;
  case BREATHVAL:
    Serial.print("Sensor monitored the current breath rate value is: ");
    Serial.println(radar.breath_rate, DEC);
    Serial.println("----------------------------");
    break;
  case BREATHWAVE:
    Serial.print("The breath rate waveform(Sine wave) -- point 1: ");
```

```
        Serial.print(radar.breath_point_1);
        Serial.print(", point 2 : ");
        Serial.print(radar.breath_point_2);
        Serial.print(", point 3 : ");
        Serial.print(radar.breath_point_3);
        Serial.print(", point 4 : ");
        Serial.print(radar.breath_point_4);
        Serial.print(", point 5 : ");
        Serial.println(radar.breath_point_5);
        Serial.println("----------------------------");
        break;
    }
  }
  delay(200);
}
```

Listing2. Setup

The setup function initializes the serial port and the radar module. It also sets the radar module to real-time transmission mode.

The breathing and heart rate data from the radar module are read by the loop function by repeatedly using the Breath_Heart() method. The code then verifies the value of sensor_report to ascertain the kind of data that is accessible if it is not equal to 0.

The following cases are handled:

- HEARTRATEVAL: The current heart rate is printed to the serial port by the code. The code activates both LEDs if the heart rate is higher than 70. The code activates the green LED if the heart rate is greater than 50 and less than or equal to 70. The code disables both LEDs if it is not used.
- HEARTRATEWAVE: The code prints the heart rate waveform data to the serial port.
- BREATHNOR: The code outputs a message to the serial port indicating that the breathing rate is within normal range.
- BREATHRAPID: The code sends a message over the serial port indicating that the breathing rate exceeds the acceptable speed.
- BREATHSLOW: The code outputs a message to the serial port indicating that the breathing rate is below the expected pace.

- BREATHNONE: The code sends a message to the serial port indicating that there is currently no available breathing information.
- BREATHVAL: The code prints the current breathing rate value to the serial port.
- BREATHWAVE: The code prints the breathing rate waveform data to the serial port.

The code then adds a 200ms delay avoiding program jam.

After uploading the code, the serial monitor will display the following message as shown in figure 7.

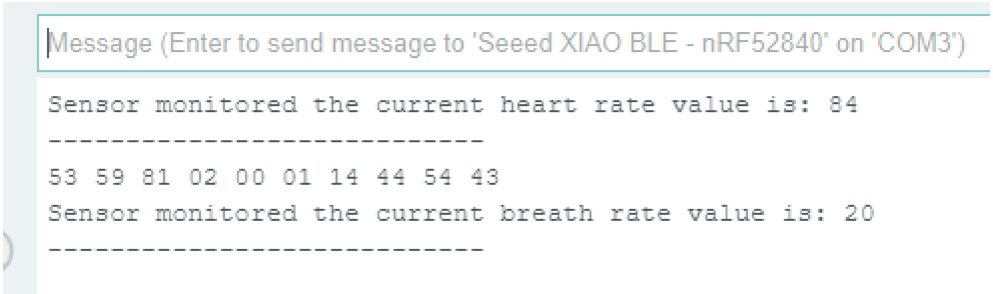

Figure 7. Serial monitor

Explanation and depiction of the frame structure:

frame header	control word	Command word	length identification		data	check code	end of frame
0X53 0X59	Control	Command	Lenth_H	Lenth_H	Data	Sum	0X54 0X43
2 Bytes	1 Byte	1 Byte	1 Byte	1 Byte	nByte	1 Byte	2 Bytes

Figure 8. Frame structure definition. as indicated in the user manual [4,8].

Frame structure description as shown in Figure 8:

a. Header Frame: 2Byte, set as 0X53, 0X59.
b. Control word: 1 Byte.
c. Command word: 1Byte.
d. Length identification: 2Byte, matching the exact byte length of the data.
e. Data: n Byte, determined by the specific function requirements.
f. Check code: 1 Byte, (Check code calculation: frame header + control word + command word + length identifier + data).

g. Frame end : 2 Byte, constant at 0X54, 0X43.
[4].

5 Experimental Results

5.1 Range performance

The actual prototyping and assembling and testing of both 24GHz and 60 GHz systems were conducted in the Electronics Laboratory of Metropolia UAS as shown in figure 9 and 10 below.

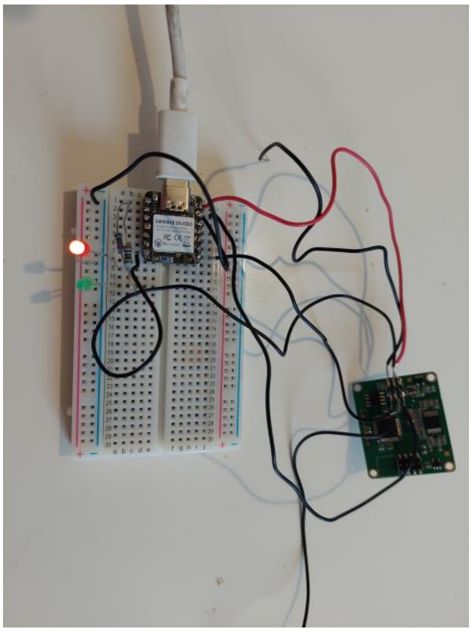

Figure 9. 24GHz mmWave sensor.

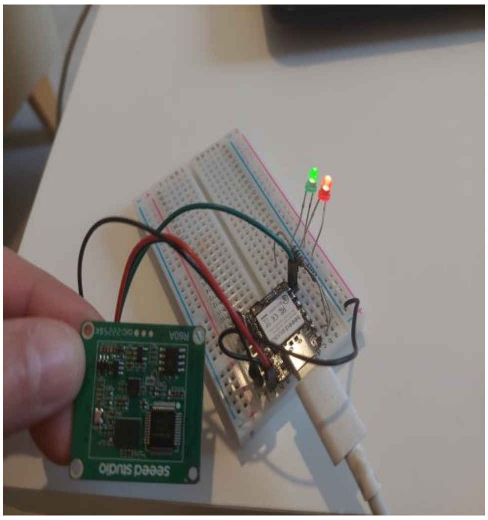

Figure 10. 60GHz mmWave sensor.

Range performance of the 24GHz mmWave sensor:

- Detection range for moving personnel: 13 meters.
- Perceived distance for stationary personnel: 5 meters.
- Horizontal radar detection angle: 90°.
- Pitch radar detection angle: 60°.

Range performance of the 60GHz mmWave sensor:

- Breath detection distance: 0.4-2 meters.
- Heartbeat detection distance: 0.4-2 meters.

5.2 Penetration performance

The 24GHz have a better penetration then the 60GHz, due to the lower frequency. This is because lower frequency waves have longer wavelengths, which can better penetrate materials such as fog, rain, and snow. 60GHz radar has higher frequency waves, which have shorter wavelengths and are more likely to be scattered by these materials.

Temperature, light, dust, and other environmental factors do not affect the radar's performance significantly. Radar operates using electromagnetic waves, which are not affected by these factors.

5.3 Resolution performance

The resolution of a 24GHz radar sensor can be as low as 10 cm, but it can be as high as 1 cm. and the resolution of a 60GHz radar sensor can be as low as 1 cm, but it can be as high as 0.1 cm.
Overall, 60GHz radar sensors have higher resolution than 24GHz radar sensors. This makes them well-suited for applications where it is important to distinguish between small objects. 24GHz radar sensors are better suited for applications where resolution is not as critical, but range and penetration are important.

6 Conclusion

This thesis work has presented a comprehensive comparison of 24 GHz and 60 GHz mmWave radar sensors. In the thesis work 24 GHz and 60 GHz mmWave radar systems were also designed and implemented and their performance in terms of range, resolution, and penetration.
The key findings of this thesis work are as shown in table 2.

Table 2. Comparison of the 24GHz and 60GHz radars:

Feature	24GHz	60GHz
Frequency	24-24.5GHz	58-63.5GHz
Wavelength	12.5 mm	5 mm
Penetration	Better	Worse

Feature	24GHz	60GHz
Resolution	Lower	Higher
Range	12 m	0.4-2 m
Cost	30 €	40 €

Based on these findings, the following conclusions can be drawn: the 24 GHz mmWave radar is better suited for applications where range, penetration, and cost are important, such as automotive, security, and manufacturing. and the 60 GHz mmWave radar is better suited for applications where resolution and interference immunity are important, such as medical imaging and telecommunications.

The thesis work has also made the following contributions to the field of mmWave radar:

- Provided a comprehensive comparison of 24 GHz and 60 GHz mmWave radar sensors, which is a valuable resource for researchers and engineers working in this field.
- Designed and implemented 24 GHz and 60 GHz mmWave radar systems, which can be used as a reference for developing new mmWave radar applications.
- Evaluated the performance of 24 GHz and 60 GHz mmWave radar systems in terms of range, resolution, and penetration, which provides valuable data on the performance of these sensors in real-world conditions.

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