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Development of a Zigbee-Based Tyre Pressure Monitoring System

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ABSTRACT

Tyre pressure monitoring systems (TPMS) are crucial in vehicle safety and performance. Direct TPMS use sensors within the tyre assembly for real-time monitoring of the tyre pressure and transmits it to report on an onboard display. Most TPMS technology uses 315 or 434 MHz Ultra High Frequency (UHF) Signal. In Nigeria, this frequency is used in the television spectrum which could result in interference. This paper, used an innovative low-power, low-cost ZigBee alternative to develop the TPMS. It covers the design, implementation and testing of the TPMS. The system comprises ZigBee sensors placed in the tyre assembly to measure tyre pressure and temperature and transmit the data to a ZigBee coordinator in the car. In turn, the ZigBee coordinator sends the aggregated data to a graphical Liquid crystal display, (GLCD) to show the real-time data of each tyre to the driver. A GSM module helps report the tyre's state to the user if the vehicle is parked and the tyre pressure is below 26 psi. The hardware circuit was designed in Proteus 8.7 and the printed circuit board (PCB) for the transmitter and receiver was developed and fabricated. MPXHZ6400AC6T1 piezoresistive pressure sensor and DS18B20 temperature sensor were used to sense the tyre pressure and temperature respectively. The software was developed using the C programming language. The developed system was installed in a 2000 model-year Toyota Camry for operational testing. A standard gauge was used to measure the tyre pressure and compare it with the developed system to determine the accuracy of the TPMS data. The results show the accuracy of the TPMS data. Future work will explore sensor accuracy optimizations and integration with advanced vehicle diagnostics systems and a mobile application.

1. INTRODUCTION

Tyre is the only part of a vehicle that makes contact with the road (Li *et al*., 2017). It is important to consider the tyre pressure of any vehicle as it will ease driving comfort and enhance the safety of the driver and passengers (Toma *et al*., 2018). Underinflated tyres lead to excessive thread wear around the shoulder, which reduces the tyre's lifespan. On the other hand, an overinflated tyre causes excessive inner tread wear. Properly inflated tyres result in the best tread wear.

The problem of improper tyre pressure can be addressed with a tyre pressure monitoring system (TPMS).

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There are two types of TPMS: Indirect and direct TPMS. Indirect TPMS uses other sensory systems in the vehicle to estimate the tyre pressure. It has the advantage of not using additional sensors which reduces its cost but it is not as accurate as the direct TPMS (Svensson *et al*., 2017; Wang *et al*., 2017; Zhao *et al*., 2023). Direct TPMS uses sensors attached to the tyre to read the actual tyre pressure making it more accurate (Chen *et al*., 2012; Mathai and Ranjan, 2015; Mule and Ingle, 2017; Silalahi *et al*., 2019; Xiangjun, 2017). However, the sensors are battery powered which limits their useful life (Ho *et al*., 2009; Kang *et al*., 2017).

TPMS is prevalent in the US, UK, China and Europe but not in Nigeria. While there are millions of vehicles in Nigeria, most are not equipped with a TPMS because they are older models. The ratio of new vehicles to used vehicles in Nigeria is 1:134 and 63% of the used vehicles are over 11 years old (Ologunagbe, 2022). This poses a serious risk to vehicle users especially for commercial vehicles because of the frequency of their use. The lack of TPMS has dramatically increased the number of tyre failures associated with such vehicles. Sometimes fatal accidents have resulted from abnormal tyre pressure. According to available statistics in Nigeria, tyre-related issues are the leading cause of accidents after human factors (Afolabi and Gbadamosi, 2017; NRSS, 2013). The work in NRSS (2013) shows a steady rise in road traffic accidents caused by tyre bursts. The statistics were 5.6% in 2008, 6.5% in 2009, 4.6% in 2010, 8% in 2011 and 9.2% in 2012. Oyeyemi *et al*. (2022) also surveyed tyre-related crashes. The statistics were 8.38% in 2011, 9.24% in 2012, 7.40% in 2013, 7.24% in 2014, 6.73% in 2015, and 6.10% in 2016. These statistics show why monitoring tyre pressures in Nigeria is crucial as it will help reduce accident occurrences from tyre-related causes.

1.2 Related Works

Zeng and Hubing (2012) investigated the effect of a vehicle body on the electromagnetic propagation of signals in a TPMS antenna. The study modelled a whip and loop antenna in HFSS and studied the effect of the vehicle body on the antenna signal propagation. It was shown that the vehicle body should be considered in the design of a TPMS antenna. The work only covered the simulated modelling of a TPMS antenna. Huang (2013) designed a TPMS system using an SP37 sensor. The developed TPMS was installed and tested in a car. The system used the allocated 315/434 MHz radio frequency signal. Vasanthara and Krishnamoorthy (2016) designed a system-on-chip (SoC) TPMS that uses Bluetooth technology. It was simulated using Proteus software but not developed or tested in a moving vehicle.

The work of (Kolodgie *et al*., 2017) was on the acceleration-based timing of TPMS to increase the battery life of the receiver and provide better security. The study observed that packets from the present TPMS receiver are not encrypted and the transmission is independent of the wheel orientation. It was noted that such an approach lends itself to spoofing attacks and the vehicle can be tracked by an attacker as each tyre sensor's unique identification (UID) is broadcast. However, the TPMS was not developed.

Silalahi *et al*. (2019) designed a tyre pressure monitoring system using a pressure sensor base. The output of the TPMS was used to control the operation of a compressor. If the tyre's pressure is reduced below a set point, the compressor is activated to pump the tyre. The tyre pumping pressure could not exceed 25 psi due to the back pressure from the tyre. The test was carried out on a stationary tyre only.

In (Sivaraos *et al*., 2019) a LabVIEW system was developed to retrieve the pressure and temperature data from a TPMS sensor and auto-plot it against time. The TPMS sensor was installed in all four tyres of the car and a Laptop with LabVIEW software installed was connected through an RS232 to USB connector to the LCD receiver unit. Dynamic tests were carried out and the result showed that the LabVIEW interface could monitor the pressure and temperature in real time and auto-plot the graph of pressure and temperature against time respectively. Detailed design of the TPMS sensor and receiver were not presented.

Gryś (2019) conducted research on the measurement and calibration of pressure sensors for TPMS. An experimental workbench was set up in which the tyre sensor was placed inside the tyre and the receiver unit was connected to a laptop. A multipoint calibration method was used to get the results. The result was embedded in the software developed which could be used by other hardware platforms with USART. The work did not develop the TPMS transmitter and receiver used in the experimentation.

Some work only considered TPMS operating at 434 MHz and 315 MHz. The previous papers analyzed the development of an antenna operating at 2.4 GHz and the effect of the wheel and tyre on signal propagation (Enalume, *et al*., 2022a; Enalume, *et al*., 2022b). Another previous paper developed an efficient battery management system for the TPMS transmitter (Enalume and Ogbeide, 2023). In this paper, TPMS using ZigBee technology at 2.4 GHz with an adequate alarm notification and reporting system was designed and developed. A reporting system for the state of the tyre, when the ignition is OFF if the pressure has reduced below a setpoint, was implemented. The use of the device will reduce the rate of tyre-related accidents in Nigeria.

2. MATERIALS AND METHODS

2.1 TPMS Module Design

The TPMS module consists of the transmitter and the receiver. Shown in Figure 1, is the block diagram of the TPMS transmitter consisting of sensors for sensing the pressure and temperature of a tyre, a microcontroller for data processing, and an XBEE module which acts as a transceiver. Figure 2 shows the TPMS receiver block diagram with an XBEE module to receive the data transmitted from each tyre, a microcontroller to process the information, and an LCD to display the output. Other accessories include a memory card to store the data with a time-stamp, and a USB module to interface the system with a computer having a custom application, to access logged data. The alert mechanism consists of alarm units for audible notification, and a GSM modem for SMS alert if a parked car's tyre pressure is below a set threshold. The design specifications for the range of tyre pressure in this work are shown in 2.2 Transmitter Unit Circuit Design

Figure 4 shows the complete circuit diagram of the transmitter unit. The PIC12F1840 microcontroller, an 8-pin microcontroller was used in this work. It processes the pressure and temperature data and also does the analogue to digital conversion (ADC). The microcontroller is also responsible for the transmitter unit's sleep and wake-up instructions. PIC microcontroller was used because of its low power consumption and high-performance ability. It is small in size and can effectively interface with all the peripherals needed in the TPMS transmitter unit.

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ZigBee technology was used to communicate between the receiver and transmitter units. Figure 3 shows the ZigBee network topology that is used in this research. A star topology was deployed with the receiver section as the ZigBee coordinator and the transmitter units as the ZigBee end devices. There are five transmitter units, one for each tyre, including the spare. The TPMS receiver unit is installed in the car where the driver can see the status of each tyre.

Table 1: Design specification for tyre pressure

Status	Pressure range (psi)
Underinflation	<29
Normal pressure	29 – 40
Overinflation	> 40

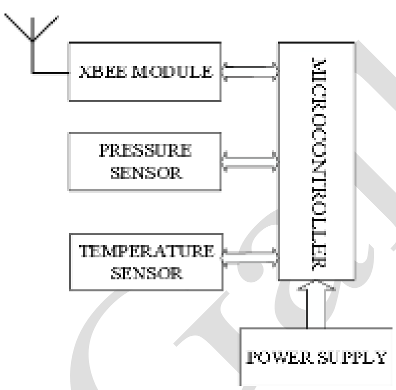

Figure 1: Block diagram of the TPMS transmitter

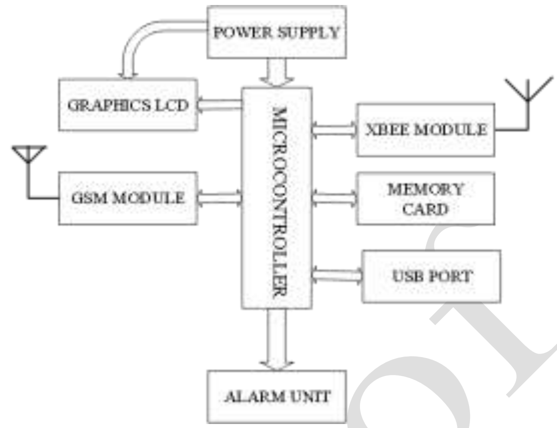

Figure 2: TPMS Receiver block diagram

2.2 Transmitter Unit Circuit Design

Figure 4 shows the complete circuit diagram of the transmitter unit. The PIC12F1840 microcontroller, an 8-pin microcontroller was used in this work. It processes the pressure and temperature data and also does the analogue to digital conversion (ADC). The microcontroller is also responsible for the transmitter unit's sleep and wake-up instructions. PIC microcontroller was used because of its low power consumption and high-performance ability. It is small in size and can effectively interface with all the peripherals needed in the TPMS transmitter unit.

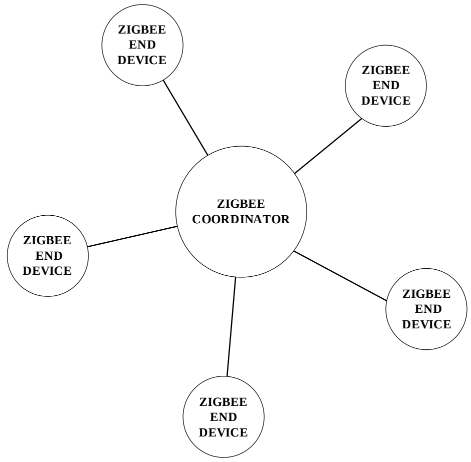

Figure 3: ZigBee Star Topology Network

The pressure sensor used in this design was the MPXHZ6400AC6T1 piezoresistive pressure sensor. The output pin 4 of the MPXHZ6400AC6T1 piezoresistive pressure sensor is connected to port RA0 (pin 7) of the microcontroller. The temperature sensor used was the DS18B20. Pin 2 of the DS18B20 is connected to port RA1 (pin 6) of the microcontroller which serves as the input pin for the analogue temperature data as well as an ADC.

Pin 2 (DO-Data Out) of the XBEE module is interfaced with pin 2 (USART asynchronous receive) of the microcontroller and it is used to transmit data from the XBEE module to the PIC12F1840 microcontroller. Pin 3 (USART asynchronous transmit) of the microcontroller is connected to pin 3 (DI-Data In) of the XBEE module to receive data from the module. The transmit data of the microcontroller is connected to the received data of the XBEE module. In contrast, the microcontroller's receive data is connected to the transmit data of the XBEE module. The microcontroller works with 5V, but the XBEE module data lines work with 3.3 V, so there is a need to step down any voltage signal from the microcontroller to the XBEE module achieved by using a 3.3k and 2.2k resistor network. (See Equations (1))

Design for the XBEE module

$$V_{10} = V_3 \frac{R_2}{R_2+R_3} \tag{1}$$

Where,

V_{10} = Input voltage to pin10 of XBEE module

V_3 = 5 V (Output voltage from pin3 of the PIC12F1840 microcontroller)

$$V_{10} = V_3 \frac{R_2}{R_2+R_3} = 5\frac{3.3}{3.3+2.2} = 3\text{ V}$$

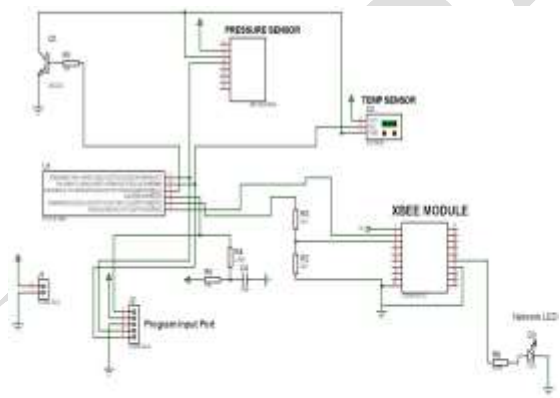

Figure 4: Complete circuit diagram of the transmitter unit

2.3 The Receiver Circuit Design

The TPMS receiver module comprises the power supply, processor, display, communication, storage and alert units. Figure 5 is the circuit diagram of the receiver unit, showing how the different sub-units are connected to the microcontroller. The microcontroller used for the receiver unit was PIC18F46K22. It is a 40-pin microcontroller. It has two USART (Universal Sequential Asynchronous Receiver Transmitter) making it easily interface with the XBEE module, GSM modem and USB module and is powered by a 5 VDC. The five ports of the microcontroller provide enough interface for all the circuit components.

The GLCD was chosen to display appropriate graphics and tyre parameters. The eight data lines, PINs 11 – 18 of the 240X128 DOT matrix

GLCD (Graphic liquid crystal Display) are interfaced to port D, PINs 19 – 22, 27 – 30 data I/O (Input/Output) ports of the microcontroller. The data write (WR), data read (RD), enable (CE), data/instruction select (C/D) and reset (RST) of the GLCD were interfaced to PINs 15(C0), 16(C1), 34(B1), 35(B2) and 36(B3) of the microcontrollers, respectively. Q2 is an IRF1010E MOSFET used to turn ON/OFF the GLCD backlight. The GLCD consumes so much energy. Turning it OFF when not in use conserves energy and extends the lifetime of the LEDs. Resistor R5 (330R) limits the current flowing through the LED that produces the LCD backlight. The design consideration for choosing R5 is given in Equation (2). Resistors R23(10K) and R24(100k) condition the High and Low voltage signals that drive Q2. The gate-to-source capacitor tries to charge to the input voltage of the MOSFET when it is ON. In the process, the capacitor draws a lot of transient currents which could damage the microcontroller. To prevent this a series resistor R23 is connected between the microcontroller and the gate of the MOSFET. (See Equation (2)) Variable resistor RV1(10k) is used to adjust the contrast of the graphics display as recommended in the datasheet.

Drain resistor R_D is given as:

$$\boldsymbol{R_D = R_5 = \frac{V_{DD}}{I_D}} \tag{2}$$

$V_{DD} = 5$ V

$I_D = 15$ mA given in the datasheet

$$\boldsymbol{R_D = R_5 = \frac{5}{15m} = 333.33\ \Omega}$$

R_5 was chosen as 330 Ω

PIN 17 of the microcontroller is at 5 V, 20 mA level.

$$\boldsymbol{R_{23} = \frac{V}{I} = \frac{5}{20m} = 250\ \Omega}$$

The buzzer is interfaced to PIN 33(RB0) through a transistor, Q1 and a 10k current limiting resistor, R14. The transistor is driven to saturation by a HIGH signal through the base resistor R14. This action grounds the buzzer, making the 12 V to be applied across it. The buzzer sounds an alarm when there is abnormal pressure. PIN 8(E0) is connected to the GSM modem, and PC communication modules transmit pins through relay RL2. The receive pin of the GSM modem and the PC communication module is connected to PIN9(E1) through relay RL3. The GSM modem as seen in **Error! Reference source not found.** is used to send SMS to the driver's mobile device if the tyre pressure is above 40 psi or below 29 psi. The PC module provides a path to retrieve stored data using a computer connected to the USB port.

The Pin 2 (DOUT) of the XBEE module is interfaced with Pin 26 (RX1) of the microcontroller. It transmits data from the XBEE module to the PIC18F46K22 microcontroller. Pin 25 (TX1) of the microcontroller is connected to the DIN (pin 3) of the XBEE module to receive the module's data. The transmit pin of the microcontroller is connected to the receive pin of the XBEE module. In contrast, the microcontroller's receive pin is connected to the transmit pin of the XBEE module. The 2D and 3D PCB layout of the TPMS is shown in Figure 6.

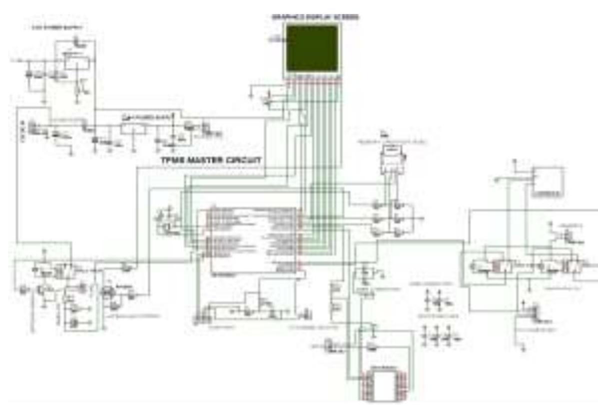

Figure 5: Receiver section circuit diagram

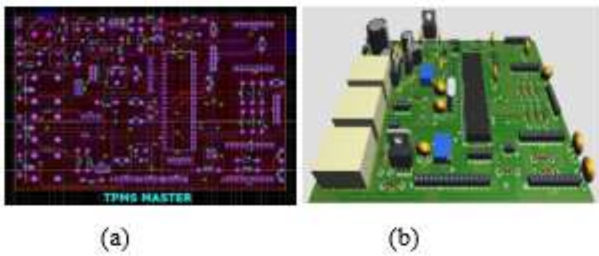

Figure 6: (a) 2D and (b) 3D PCB layout design of the receiver unit

2.4 Implementation of the TPMS

The software program of the receiver and transmitter unit was written in C language and burnt into the microcontroller using the Pickit3 programmer via the ICSP (In-Circuit Serial Programming) port.

Figure 7 shows the operational flowchart of the receiver partially in control without an accelerometer in the transmitter unit. The system initializes when the ignition is turned ON and starts charging the rechargeable battery of the receiver unit. The receiver unit waits to receive the TPMS sensor data. Upon receipt of the sensor data, it sends an ACK containing the timing schedule, the 64-bit MAC address of the transmitter ID and the source and destination 16-bit address. The TPMS sensor then maintains or updates its timing schedule depending on the information received from the receiver. During this period, data transmission is done every 10 minutes. Each transmitter sends its data to the receiver at this rate and the receiver displays the pressure and temperature of each tyre. The values of the tyre pressure and temperature are displayed on the LCD. If any tyre's pressure is above 40 psi or below 29 psi, it activates the buzzer to alert the user. An SMS alert is also sent to the user's mobile phone.

When the ignition is turned OFF, the system initializes and turns OFF the GLCD. The process follows the same procedure as when the ignition was turned ON. However, the rate of transmission is reduced from every 10 minutes to every 1 hour. During this period, the status of the tyres are logged by the SD card but is not displayed on the GLCD. When an abnormal pressure is detected, the buzzer sounds an alarm, and the GSM modem sends a status notification to the user's mobile device. The addition of SMS notification is an improvement over existing TPMS technology and it helps to forestall the problem of having a flat tyre only to discover when the car is to be driven.

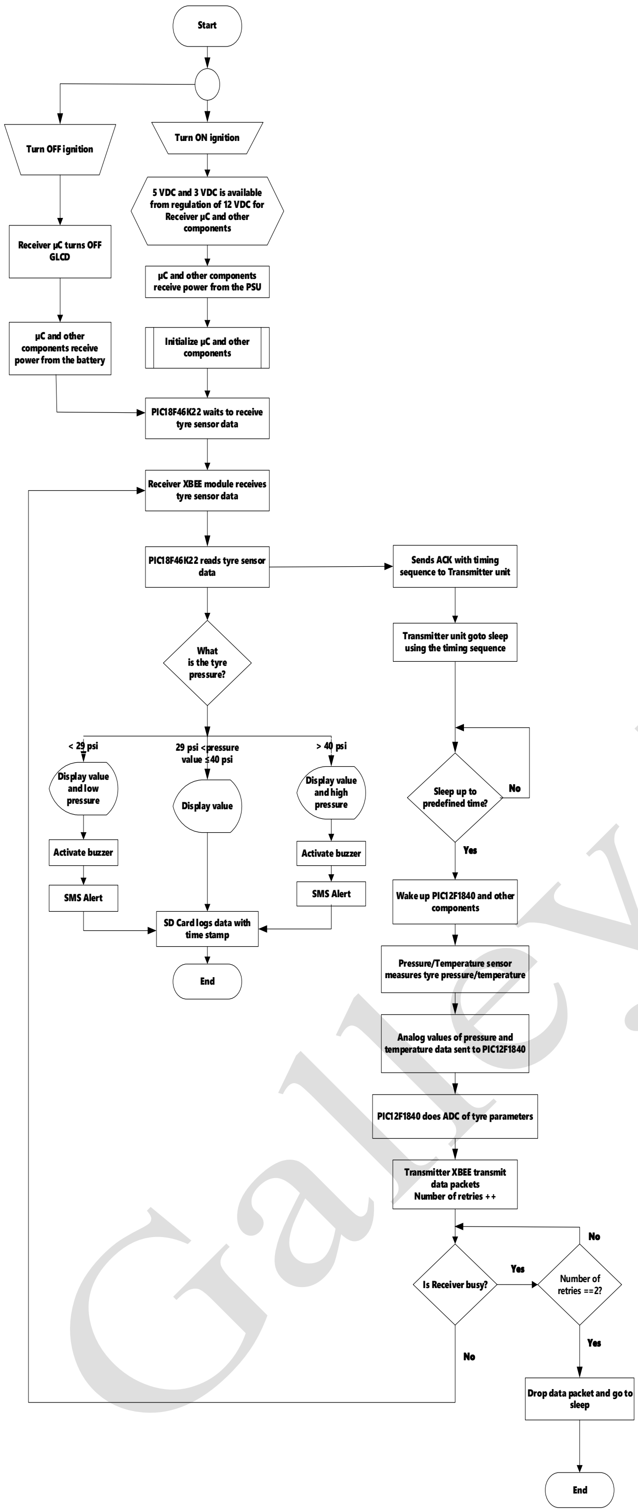

Figure 7: Operational flowchart of TPMS without an accelerometer in the transmitter unit

After the successful design of the TPMS modules, the hardware was developed. The components were soldered to their respective vias and continuity tests were carried out. After the hardware units were developed, it was packaged and installed on a Toyota Camry 2000 model for six months of operational testing. Figure 8 shows the completed TPMS modules and their installation.

Figure 8: Implementation and installation of the developed TPMS

3. RESULTS AND DISCUSSION

3.1TPMS Transceiver Tests and Results

The developed TPMS monitored the tyre pressure and temperature and reported it on a GLCD for the user to see. Figure 9 shows the snapshot of the TPMS display. An accuracy test was conducted by comparing the reading of the developed TPMS to a standard pressure gauge. This test was conducted to determine the accuracy of the data transmitted from the tyres. The results of the test are shown in Table 2. The percentage error was determined to be 0.83 % to 1.38 %, showing highly accurate data.

Figure 9: Snapshots of the TPMS display

Table 2: Tyre pressure reading in psi of the developed TPMS and a standard gauge

FR	DIGITAL GAUGE	FL	DIGITAL GAUGE	RL	DIGITAL GAUGE	RR	DIGITAL GAUGE
40	40	34	34	35	35	38	37
38	39	36	37	37	37	36	36
35	35	32	34	34	33	35	34
37	36	38	38	36	37	33	33
32	32	40	40	38	40	36	37
30	30	37	36	32	32	38	38
36	37	33	34	34	36	32	34
34	35	38	39	37	38	37	38
36	36	36	37	36	35	33	35
34	35	34	34	33	33	40	39

$$FR\ \%error = \frac{Digital\ guage - FR}{Digital\ guage} \times 100$$
$$= \frac{355 - 352}{355} \times 100 = 0.85\%$$

$$FL\ \%error = \frac{Digital\ guage - FL}{Digital\ guage} \times 100$$
$$= \frac{363 - 358}{363} \times 100 = 1.38\%$$

$$RL\ \%error = \frac{Digital\ guage - RL}{Digital\ guage} \times 100$$
$$= \frac{356 - 352}{356} \times 100 = 1.12\%$$

$$RR\ \%error = \frac{Digital\ guage - RR}{Digital\ guage} \times 100$$
$$= \frac{361 - 358}{361} \times 100 = 0.83\%$$

3.4.1 TPMS Remote Reporting System

The remote reporting system alerts the user if the tyre pressure lies outside 29-40 psi by sending an SMS to the user's mobile. Figure 10 shows the result of the SMS notification.

Figure 10: Snapshots of The SMS Notification

3.4.2 TPMS Logged Data for Analysis

The operational test was done for six months. The TPMS data was saved to a memory card in the receiver unit. TPMS data with timestamp was logged in the memory card, and a sample of the data is shown in

Table 3. The results show that the transmitter units measured the data and transmitted the same to the receiver unit, which was saved to the memory card. There was a daily rise and

drop of 2 psi in the tyre pressure. The alarm status indicates the state of each tyre pressure. If it is OFF, it shows that the pressure is normal but if it is ON, it indicates an abnormal pressure either higher than 40 psi or less than 29 psi.

Table 3: Sample TPMS data stored in the memory card

DAY	DATE	TIME	TYRE ID	TYRE PRE (psi)	TYRE TEMP (Deg. Cel)	ALARM STATUS
THURSDAY	02.06.2022	00.00.02	FR	33	23	OFF
THURSDAY	02.06.2022	00.00.05	FL	33	23	OFF
THURSDAY	02.06.2022	00.00.07	RL	33	22	OFF
THURSDAY	02.06.2022	00.00.11	RR	33	22	OFF
THURSDAY	02.06.2022	00.00.14	SP	32	20	OFF
THURSDAY	02.06.2022	00.10.05	FR	33	23	OFF
THURSDAY	02.06.2022	00.10.07	FL	33	23	OFF
THURSDAY	02.06.2022	00.10.11	RL	33	22	OFF
THURSDAY	02.06.2022	00.10.13	RR	33	22	OFF
THURSDAY	02.06.2022	00.10.18	SP	32	20	OFF
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
THURSDAY	02.06.2022	23.41.19	FL	35	31	OFF
THURSDAY	02.06.2022	23.41.20	RL	33	30	OFF
THURSDAY	02.06.2022	23.41.21	RR	33	30	OFF
THURSDAY	02.06.2022	23.41.22	SP	32	25	OFF
THURSDAY	02.06.2022	23.51.21	FR	35	30	OFF
THURSDAY	02.06.2022	23.51.22	FL	35	30	OFF
THURSDAY	02.06.2022	23.51.23	RL	33	29	OFF

4. CONCLUSION

The test results of the developed TPMS show that it can effectively monitor the tyre pressure and temperature and alert the driver when there is abnormal pressure. The developed TPMS has a percentage error of 0.83 % to 1.38 %. The TPMS measured and logged the tyre pressure and temperature accurately. It was also observed that there was a daily rise and drop of about 2 psi in the tyre pressure. The developed TPMS could alert the vehicle user through the mobile phone when any of the tyres have gone below or above the threshold value of 29 psi or 40 psi respectively. This approach would help address the challenge of having a flat tyre only to discover when the vehicle is to be driven. The GLCD displayed the TPMS data, to help the driver know the tyre pressure and temperature. The ZigBee TPMS was successfully developed to efficiently measure the tyre pressure and temperature and alert the driver.

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