1.Juwita MOHD SULTAN*[1], 2. Nurul Najihah KAMARUZAMAN[1], 3. Amir Rashid CHAUDHARY[2], 4. Azdiana Md YUSOP[1] 5. Zahariah MANAP[1] 6. Darmawaty MOHD ALI[3]

Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia (1)
Electrical Engineering Department, COMSATS University, Islamabad, Pakistan (2)
School of Electrical Engineering, College of Engineering, UiTM Shah Alam, 40450 Shah Alam, Selangor,Malaysia (3)
ORCID: 0009-0009-6133-7567

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Precision Indoor Positioning with Ultra-Wideband (UWB) Technology

Abstract *Ultra- Wideband (UWB) is a radio-based communication technology that allows for quick and reliable data transmission over short distances. This paper explores the application of UWB in indoor localization systems tailored for emergency response operations. A persistent challenge during emergency rescues is the loss of communication and tracking capabilities for responders within a building, making it impossible for those outside to pinpoint their exact locations. The aspiration of this project is to develop a device that could track the indoor location using a microcontroller and the DWM 1000. This system will be designed to track and collect data from on-scene situations such as collapsed buildings, landslides, and other natural disasters. On exact measurements of the transmitted time of arrival (ToA) and time difference of arrival (TDoA), the system is built. While TDoA merely deals with relative time for all receivers, ToA requires accurate knowledge of the synchronizing and transmitting times between the transmitter and receiver. Aside from that, measurements will be used to evaluate the performance of the DWM 1000 UWB parameters. Beyond its utility in emergency response, the system empowers precise control and localization of first responders using UWB technology, providing fast, accurate, real-time object tracking and tracing for indoor applications. The system's versatility extends to assisting visually impaired individuals in navigating unfamiliar spaces, aiding in emergency evacuations in smoke-filled environments, and enhancing child safety in crowded venues.*

Streszczenie. *Ultraszerokopasmowy (UWB) to technologia komunikacji radiowej, która pozwala na szybką i niezawodną transmisję danych na niewielkie odległości. W artykule omówiono zastosowanie UWB w wewnętrznych systemach lokalizacyjnych dostosowanych do działań ratowniczych. Stałym wyzwaniem podczas akcji ratowniczych jest utrata możliwości komunikacji i śledzenia ratowników w budynku, uniemożliwiająca osobom znajdującym się na zewnątrz dokładne określenie ich lokalizacji. Aspiracją tego projektu jest opracowanie urządzenia, które mogłoby śledzić lokalizację w pomieszczeniach zamkniętych za pomocą mikrokontrolera i DWM 1000. System ten będzie przeznaczony do śledzenia i gromadzenia danych z sytuacji na miejscu zdarzenia, takich jak zawalone budynki, osuwiska i inne klęski żywiołowe . Na podstawie dokładnych pomiarów transmitowanego czasu przybycia (ToA) i różnicy czasu przybycia (TDoA) budowany jest system. Podczas gdy TDoA zajmuje się jedynie względnym czasem dla wszystkich odbiorników, ToA wymaga dokładnej wiedzy o czasach synchronizacji i transmisji pomiędzy nadajnikiem a odbiornikiem. Oprócz tego pomiary zostaną wykorzystane do oceny parametrów DWM 1000 UWB. Oprócz swojej użyteczności w sytuacjach kryzysowych, system umożliwia precyzyjną kontrolę i lokalizację osób udzielających pierwszej pomocy przy użyciu technologii UWB, zapewniając szybkie i dokładne śledzenie obiektów w czasie rzeczywistym w zastosowaniach wewnętrznych. Wszechstronność systemu obejmuje pomoc osobom niedowidzącym w poruszaniu się w nieznanych przestrzeniach, pomoc w ewakuacji awaryjnej w środowiskach wypełnionych dymem oraz poprawę bezpieczeństwa dzieci w zatłoczonych miejscach.* (***Precyzyjne pozycjonowanie w pomieszczeniach dzięki technologii ultraszerokopasmowej (UWB)).***

Keywords: Ultra-Wideband (UWB), DWM 1000 UWB Sensor, Time of Arrival (ToA), Time Difference of Arrival (TDoA)
Słowa kluczowe: Ultraszerokopasmowy (UWB), czujnik DWM 1000 UWB, czas przybycia (ToA), różnica czasu przybycia (TDoA)

Introduction

Over the past few decades, advancements in indoor localization have revolutionized tracking technologies. While Global Positioning System (GPS) dominates outdoor positioning, indoor environments pose unique challenges due to signal attenuation from structures like roofs and walls, making GPS ineffective [1]. Indoor localization systems offer distinct advantages, aiding the visually impaired and enabling tracking of emergency responders in collapsed buildings. However, achieving precise indoor localization remains a challenge [2]. Enter ultra-wideband (UWB) technology, an emerging solution promising highly accurate indoor tracking, free from external interference or reflective obstacles [3].

UWB, characterized by its expansive bandwidth exceeding 500 MHz and a spectrum covering over 20% of its carrier frequency [4], represents a high-speed, reliable radio technology designed for short-distance data transmission. In the realm of indoor localization systems, UWB emerges as a novel technology capable of real-time tracking and data collection, with a paramount focus on achieving exceptional accuracy [5]. The unique signal properties of UWB empower it to precisely determine the position and location within indoor environments, boasting remarkable precision and accuracy within a coverage area ranging from 15 to 25 square meters [6]. Consequently, UWB stands out as the most apt choice for indoor localization systems.

Implementing UWB within indoor localization systems necessitates the identification of signal parameters exchanged between the tag and achor position. These signal parameters are measured with the utmost precision, leveraging transceiver capabilities for example the Time of Arrival (ToA), and Time Difference of Arrival (TDoA). Typically, a single signal parameter is measured for each received signal, although the potential exists to measure multiple signal parameters simultaneously, enhancing localization accuracy [7].

Indoor Localization System with UWB

Localization entails the process of determining the precise positions of individuals, equipment, and various objects. This localization process can be broadly categorized into two domains: indoor and outdoor. Indoor localization occurs within enclosed structures, encompassing settings like residences, healthcare facilities, and shopping complexes, while outdoor localization takes place in open environments, beyond the confines of buildings. The choice of specific localization systems varies depending on the unique requirements and constraints of each application [8].

Indoor localization systems operate continuously and in real-time to ascertain the exact whereabouts of objects within a physical space, as illustrated in Fig.1. Indoor localization sets forth distinct demands that set it apart from its outdoor counterpart. The indoor localization system will be judged on five key quality parameters: system accuracy and precision, coverage and resolution, latency in location updates, impact on the building's infrastructure, and impact of random errors, such as reflection and signal interference errors, on the system.

Fig.1. Positioning with Anchor Points [8]

The primary challenge in indoor localization revolves around addressing reflective environments, making it difficult to estimate distances solely based on received signal strength. Nevertheless, these challenges can potentially be circumvented through the adoption of UWB technology. UWB stands out due to its exceptional flexibility, attributed to its utilization of narrow pulses, which yield remarkably precise time resolution and, consequently, enhance localization accuracy. Within the realm of UWB technology, various signal parameters can be measured, contingent upon the transceiver's accuracy such as ToA TdoA [9].

Time of Arrival (ToA)

As seen in Fig. 2, the ToA is based on the intersection of circles for numerous transmitters. The circle's radius, which is determined using the one-way propagation time, ToA, which is directly connected to distance, displays the separation between the transmitter and receiver. The nodes must either share a clock or exchange timing data using specific protocols in order to calculate the ToA parameter for a signal moving between them.

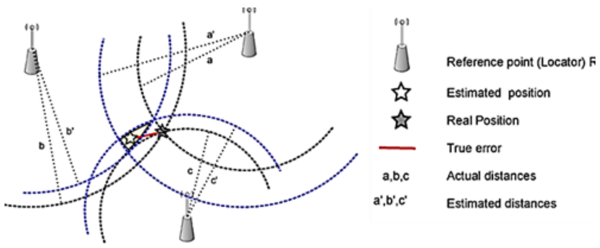
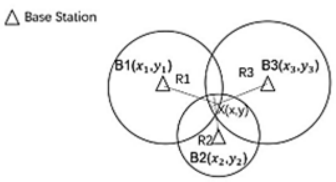


Fig.2. ToA Precision Localization Algorithms [10]

The coordinates of the reference nodes serve as the centres of all the spheres, while the distances between them and the target node serve as their radiuses. The intersection of all these spheres serves as the location of the target node. [15]. As shown in Fig. 3, the base station serves as the center of a circle with the measured distance as its radius to calculate the tag's location.



$$R1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$
$$R2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2}$$
$$R3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2}$$

Fig.3. ToA Derived Location [11]

Where (x, y) is the location of the tag, (x1, y1), (x2, y2), and (x3, y3) are the coordinates of the base stations, and R1, R2, and R3 represent the distances from the tag to the base stations, respectively. Additionally, the location estimation's aim is to determine the coordinates that are the closest to the actual location. For accuracy, the approach depends on the base station keeping its clock in sync with the tag. To complete a full cycle phase between the tag and the base station in the site verification, however, is extremely difficult. The speed of the tag may cause more inaccuracy. A restriction is the need for synchronization between the transmitter and receiver. Different time measurement techniques, such the Time Difference of Arrival (TDoA), leave this difficulty behind.

Time Difference of Arrival (TDoA)

Today compares the time difference between each anchor and each signal. As illustrated in Fig. 4, the location of the tag is determined by the difference between the arrival times of signals issued from the tag and received simultaneously by all anchors. Since only one transmitter typically operates, the many receivers can communicate and cooperate to determine the exact location of the emitter. However, this method only needs the time the signal was received and the speed during propagation; it does not require the time the signal was transmitted from the destination. The spacing between the target and the several reference points can be determined using the difference in arrival time after the signal has been received at numerous reference stations. TDoA basically assesses the variation in signal transmission times between the tag and two or more independent reference sites to determine the distance between two paths [12].

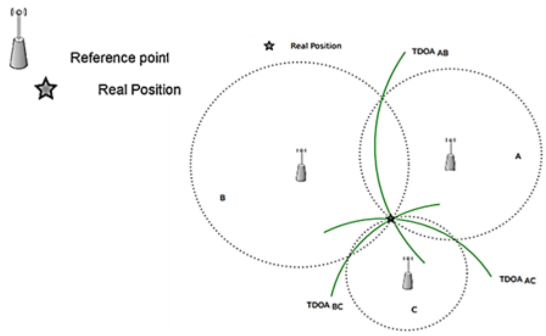
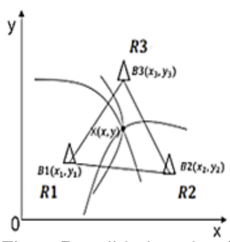


Fig.4. TDoA Precision Localization Algorithms [13]

TDoA determines the distance between two places by measuring the delay in signal transmission between the positioning tag and two additional base stations. TDoA is therefore based on the time difference between the measurements made at the ToA location. To build a hyperbola, TDoA employs the tag and the base station or anchor as the interchange site, as shown in Fig. 5.



$$R2 - R1 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$
$$R3 - R2 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} - \sqrt{(x_2 - x)^2 + (y_2 - y)^2}$$
$$R3 - R1 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} - \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$

Fig.5. Possible location for TdoA [14]

The coordinates of the base stations are (x1, y1), (x2, y2), and (x3, y3), while the coordinate of the tag is (x, y). When there are three hyperbolas, the label's exact location can be determined. The sampling clock and the signal bandwidth still have a role in the outcome of TDOA, despite the fact that it can attain excellent accuracy by merely synchronizing the base station clocks.

Analytical Method to determine ToA and TDoA

Analytical methods are essential tools in the realm of positioning and tracking systems. When it comes to determining ToA and TDoA, analytical techniques play a pivotal role. These methods provide precise ways to calculate when signals arrive at different points, enabling users to pinpoint locations and track objects with accuracy. In this context, the researcher explore the analytical methods used to extract ToA and TDoA information, shedding light on their significance in modern positioning technology.

Determining the point of convergence for all the spherical regions, where each sphere has its center anchored at the reference nodes' coordinates and its radius defined by the distances between them and the target node, provides the precise location of the target node. These spherical regions can be characterized as [15][16].

(1) $(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = m_i{}^i\,, (i = 1,2,\dots,n)$

where mi1 denotes the TDoA estimation range as (i=2,3,...,n). The true distances between the reference nodes and the target node are represented by the unknown parameters ri (i=1, 2,..., n). The number of reference nodes is n.

The reference nodes' known coordinates are (xi, yi, zi). (X, Y, Z) are the target node's coordinates, which must be identified. Therefore, (1) can be changed to

(2) $x' = x - x_1\,,\ y' - y_1\,,\ z' = z - z_1$

and

(3) $x_i{}' = x_i - x_1 \qquad (i = 2,3)$

An equation in matrix form is produced by substituting the first one (i=1) into (1) and gradually subtracting it from it for i=2, 3, etc.

(4) $\begin{bmatrix} x_2{}' & y_2{}' & z_2{}' \\ x_3{}' & y_3{}' & z_3{}' \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \frac{1}{2} \begin{bmatrix} m_1{}^2 - m_2{}^2 + x_2{}'^2 + y_2{}'^2 + z_2{}'^2 \\ m_1{}^2 - m_2{}^2 + x_2{}'^2 + y_2{}'^2 + z_2{}'^2 \end{bmatrix}$

where

(5) $y' = f_1(x')\,, z' = f_2(x')$

(6) $x'^2 + f_1(x') + f_2(x') = m_1{}^2$

Comparison between ToA and TDoA

ToA signifies the duration taken for a signal's journey from the transmitter (tag) to the receiver (anchor). Essentially, it quantifies the distance by calculating the one-way propagation time between these points. This calculation entails subtracting the time at which the signal departed from the transmitter node from the time it arrived at the receiver. Conversely, TDoA refers to the discrepancy in ToA between two signals. TDoA hinges on the temporal disparity between the arrival of a signal dispatched by the transmitter and its reception by two or more receivers. Typically, there is only one transmitter in operation, necessitating the collaboration of multiple receivers to exchange information and collaboratively determine the emitter's position. The variance in signal arrival times, synchronized among all anchors, serves as the key data point for pinpointing the tag's location [17].

Indoor localization poses unique challenges and complexities not encountered in outdoor scenarios. Unlike the relatively open spaces outdoors, indoor environments are inherently intricate due to the presence of numerous obstacles such as walls, doors, and equipment. These obstructions can significantly impact signal behavior, introducing complications like signal reflection, multipath interference, and delay issues. Indoor signal propagation typically follows a non-line of sight (NLOS) pattern, meaning that the signal cannot go from the transmitter to the receiver in a straight line. Figure 6 compares Line of Sight (LOS) with NLOS, showing how NLOS circumstances originate from a variety of obstructions found in indoor locations, which causes variable time delays reaching the receiver. The presence of these obstacles often results in substantial signal attenuation and scattering. Consequently, indoor localization demands a higher degree of precision and accuracy compared to outdoor localization.

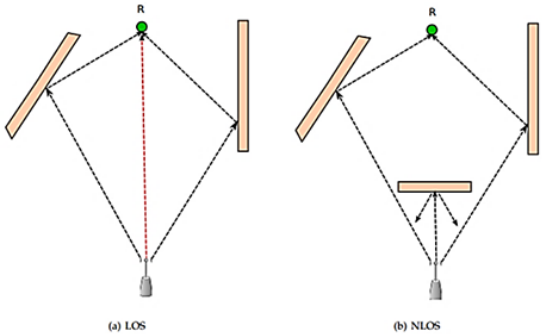


Fig.6. (a) LoS and NLoS Setup Environment [17]

Results and Performance Analysis

This project relies on six primary hardware components, namely: the DWM 1000, Logic Level Converter, GY-521 IMU Sensor MPU6050, AMS1117 3.3V Power Supply Module, Arduino Mega 2560, and Arduino UNO R3 [18]. In parallel, the primary software employed in this project is the Arduino IDE software, used for programming the system. The transmitter and reception components, which are represented by two separate parts of the hardware development, are shown in Figs. 7 and 8, respectively.

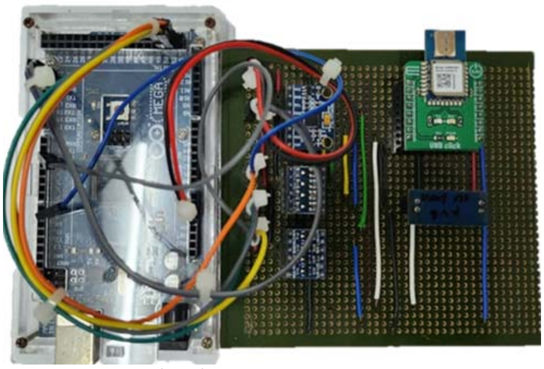


Fig.7. The Transmitter (Tag)

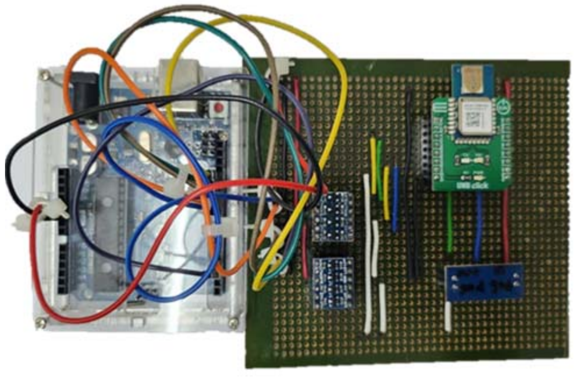


Fig.8. The Receiver (Anchor)

Site Verification and Measurement

In the indoor environment, measurements were conducted within a school hall containing various obstacles such as chairs, tables, and a whiteboard. For the LOS conditions, all obstacles were deliberately removed, allowing a clear sight between the transmitter and receiver. In this setup, the ToA parameter was measured as described in Fig.9.

Fig.9. The Measurement Environment for Indoor Scenario

Accuracy of DWM1000

The accuracy of the DWM1000 is a crucial factor on each site measurement. Therefore, the accuracy of DWM1000 is evaluated and analyzed in order to validate the performance of the DWM1000 sensor. As mentioned in literature review, the range of the accuracy percentage is defined as; over 90% is very good, between 70% and 90% is good, between 60% and 70% is acceptable, and below 60% is poor. The distance for each measurement is fixed up to 1 meter apart.

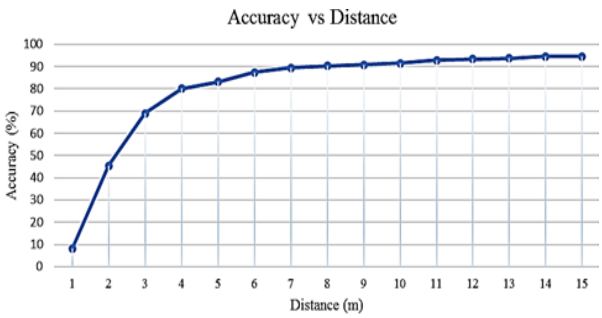


Fig.10. The accuracy of DWM1000

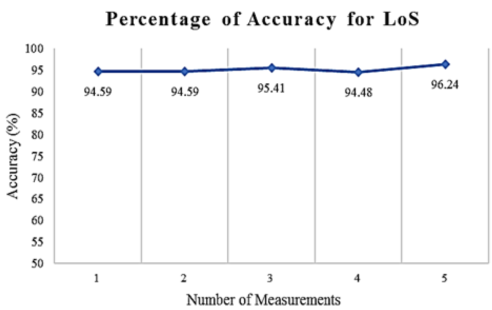


Fig.11. ToA Measurement under Line of Sight (LOS) Condition

Referring to Fig.10, we can observe a clear trend in the average accuracy percentages of the DWM1000 sensors with respect to distance. The accuracy percentages follow a distinct pattern with varying distances. Initially, in the range of 1 to 3 meters, the accuracy percentages hover around 70%, indicating an acceptable level of accuracy. However, as the distance increases, from 4 to 8 meters, the accuracy percentages stabilize and fall within the good range of 70% to 90%. Remarkably, when the distance surpasses 9 meters and extends further, the accuracy remains consistently stable and attains a very good score. This pattern serves as strong evidence that the DWM1000 UWB sensor can provide highly accurate measurements within a range of less than 15 meter, confirming its precision and reliability.

Fig. 11 illustrates the accuracy percentages of TOA readings under LOS conditions within an indoor scenario. The data reflects stability across five measurement instances, with only a marginal 1.76% variance in accuracy. The highest recorded accuracy percentage reached 96.24%, while the lowest was 94.48%.

Fig.12. The Measurement Environment for Outdoor Scenario

In this project, another important application for the DWM1000 UWB sensor is ToA measurement in an outdoor scenario as shown in Fig. 12. The measurement area comprises an open parking area with a roof. Similar experimental conditions were replicated, including both LOS and NLOS scenarios. The findings are elucidated in Fig. 13 and Fig. 14 respectively. The accuracy percentages for these measurements consistently fell within the range of 93% to 94%, which aligns with the criteria denoting a very good level of accuracy.

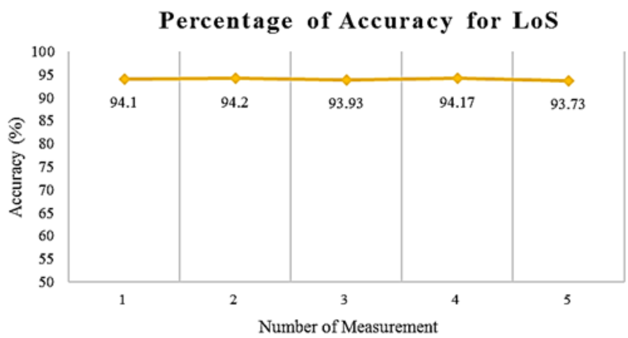


Fig.13. ToA Measurement under Line of Sight (NLOS) Condition

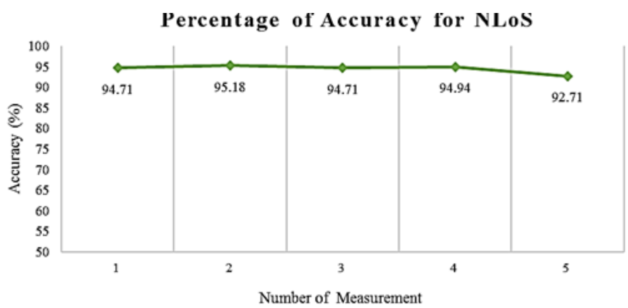


Fig.14. TDOA Measurement under Non-Line of Sight (NLOS) condition

Conclusion

In conclusion, this project has successfully developed an indoor location tracking device utilizing cutting-edge UWB technology, particularly the DWM1000 sensor. The fundamental principle behind the operation of this system involves the transmission of location data from the DWM1000 tag to the DWM1000 anchor via radio frequency communication. The anchor then calculates the distance between the transmitter and receiver based on the received signals. Two crucial parameters, namely ToA and TDoA, were central to this project. ToA relies on precise knowledge of the signal's transmission time from the tag, the exact moment it reaches a reference location, and the speed of the signal. On the other hand, TDoA involves comparing the time differences between signals received by multiple anchors. By analyzing the discrepancies in signal arrival times, the system can accurately determine the tag's location. Furthermore, the project verified measurements conducted in both indoor and outdoor scenarios, including LOS and NLOS conditions. These comprehensive tests aimed to evaluate the system's performance across various real-world conditions, further underscoring its potential utility in a wide range of applications.

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Authors: *Ts. Dr Juwita Mohd Sultan, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka.Jalan Hang Tuah Jaya, Durian Tunggal, 76100 Melaka, Malaysia. Email: juwita@utem.edu.my.*
Nurul Najihah Kamaruzaman. Email: najihahkz98@gmail.com
Amir Rashid Chaudhary. Email: amir.rashid@comsats.edu.pk
Azdiana Md Yusop. Email: azdiana@utem.edu.my
Zahariah Manap. Email: zahariah@utem.edu.my
Darmawaty Mohd Ali. Email: darma504@uitm.edu.my

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