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A Comparative Evaluation of Wi-Fi RTT and GPS Based Positioning

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ABSTRACT

Wi-Fi-based positioning technology has snowballed over the past 20 years along with the fast development and applications of smartphones for indoor positioning. On the other hand, Wi-Fi is increasingly accepted for outdoor positioning due to the availability and popularity of public Wi-Fi in global cities. Since GPS signals are often interrupted and unstable in the downtown areas with high-rise surrounded, Wi-Fi becomes an ideal positioning technology as a substitution of GPS. Especially after the release of the IEEE 802.11mc standard last year, researchers and specialists from industries were attracted immediately after the release. The new standard provides a fine time measurement protocol for us to use multiple round-trip time (RTT) rather than the received signal strength indicator (RSSI) for calculating the distance between a Wi-Fi access point (AP) and a mobile end-user device. This paper presents an evaluation and comparison study between Wi-Fi RTT and GPS based localisations in an outdoor space located in a central downtown area in Melbourne city. Based on the same testing environment and the same testing points within a central city area, both GPS and Wi-Fi RTT are tested and analysed. Results showed that the average positioning accuracies from the two technologies are 5.10 m and 1.40 m, respectively. The Wi-Fi RTT technology demonstrated a much better performance both in accuracy and stability.

KEYWORDS: GPS, Wi-Fi RTT, positioning, smartphone, LBS.

1. INTRODUCTION

The recent release of the IEEE 802.11mc standard provides us with a new era for smartphone and Wi-Fi-based localisation. As the single most popular wireless network protocol of the 21st century, Wi-Fi technology powers not only most home and business wireless networks, but also public hotspot networks (Mitchell 2019; Ta 2018). Wi-Fi and smartphone-related location-based service (LBS) and indoor positioning have gained much attention from both research and industrial communities in the recent ten years (Donovan 2013; Machowinski 2013; Elkhodr, Shahrestani, and Cheung 2016; Mohapatra, Choudhury, and Das 2014; Adams 2018; Gao, Tang, and Bai 2019; Bai et al. 2014; Bai 2016).

The advantage of the 802.11mc standard for localisation is that supports a fine-time-measurement (FTM) protocol, which allows us to calculate the distance between a smartphone and an AP using round-trip-time (RTT) of the Wi-Fi signal transmission between a smartphone and an AP. Applying the Wi-Fi RTT protocol leads to the increment of the positioning accuracy from 5-10 meters as obtained from traditional positioning methods to about 1 meter in any line-of-sight (LoS) surrounding environment (Diggelen, Want, and Wang 2018). This has brought us a great era in using smartphone-based LBS, as both hardware standard and Android application programming interfaces (APIs) are simultaneously evolving to enable an improved ranging accuracy that has not previously been possible when using smartphones and Wi-Fi.

The rest of the paper is outlined as follows: the principle of the Wi-Fi RTT protocol will be introduced in Section II. Section III will discuss the combination and conversions between geodetic and local coordinate systems and also the Wi-Fi-based multilateration process. Section IV will present the procedure of experimental tests and results analysis. Finally, the conclusion part and future work will be addressed in Section V.

2. HOW DOES WI-FI RTT WORKS

The Wi-Fi 802.11 standard provides a possible way of achieving high-accuracy positioning in a dense multipath environment, which imposes several hardware design changes in the existing WLAN chipsets in order to increase the timing resolution from the microseconds level to the nanosecond level (or even sub-nanosecond level) (Diggelen, Want, and Wang 2018). The Wi-Fi RTT is a point-to-point (P2P) single-user protocol, which includes an exchange of multiple message frames between an initiating station (ISTA) and a responding station (RSTA). The ISTA (e.g., a smartphone) attempts to measure its range to the RSTA (e.g., an AP). Obtaining an accurate time-delay estimate in a dense-multipath environment is challenging. It requires precise detection of the first signal path associated with the LoS condition between the two stations and the estimation of its arrival time (Banin et al. 2017; Yu et al. 2019). That is why the RTT protocol not entirely compatible with a non-line-of-sight (NLoS) surrounding environment currently. While Wi-Fi RTT protocol enables distance ranging between a smartphone and an AP, the whole procedure is described as follows. First, the smartphone sends an FTM request to the AP, then, the AP receives the request and returns an acknowledgement (ACK) signal to the phone terminal. After that, several FTM feedbacks are sent from the AP to the mobile terminal, and, then, the mean round-trip time is used for range calculation. This process can also be performed between several smartphones and Wi-Fi APs at the "same" time. The whole FTM RTT procedure is shown in Figure 1, in which the number of RTT (also called "burst number") can be changed to improve the FTM accuracy by providing multiple measurements within one period. Currently, the default number of RTT is 8 and the maximum

number of successful measurements is 7.

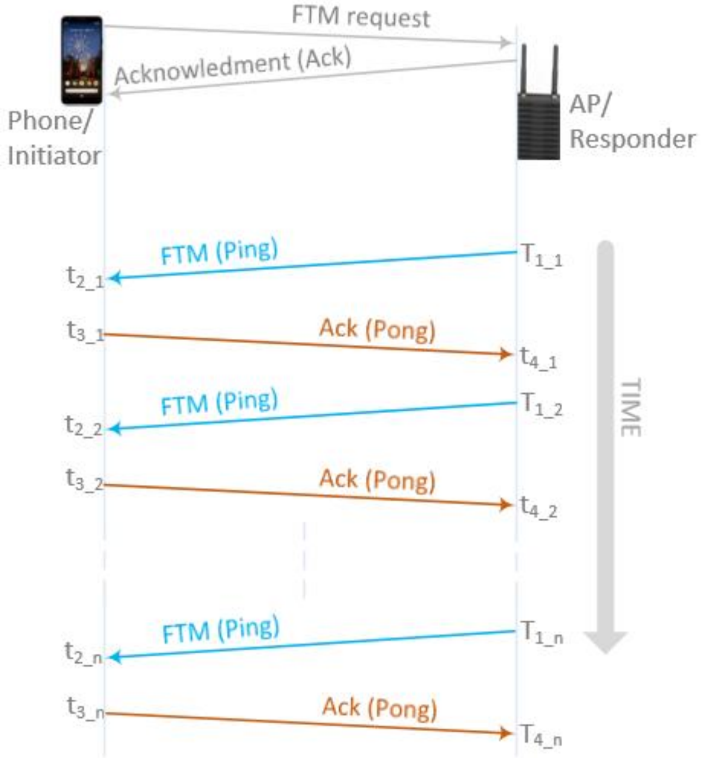


Figure 1. Principle of the FTM protocol

The mean RTT of each period is calculated by Equation (1) (Yu et al. 2019):

$$t_{RTT} = \frac{1}{N}\left(\sum_{i=1}^{N} t_{4\_i} - \sum_{i=1}^{N} t_{1\_i}\right) - \frac{1}{N}\left(\sum_{i=1}^{N} t_{3\_i} - \sum_{i=1}^{N} t_{2\_i}\right) \quad (1)$$

where:
t_{1_i} is the timestamp when the FTM framework first sent by a Wi-Fi AP;
t_{2_i} is the timestamp when the FTM signal arrives at the smartphone;
t_{3_i} is the timestamp when the smartphone returns the ACK signal to the AP;
t_{4_i} is the timestamp when the ACK signal is finally received by the AP;
N is the successful burst number (where $N > 0, N < B$); and
B is the total burst number (i.e., burst size, B = 8 by default in this research).

Generally, the protocol excludes the processing time on the smartphone terminal by subtracting (t_(3_i) - t_(2_i)) from the total round-trip time (t_(4_i) - t_(1_i)), which represents the time from the instant the FTM message is sent (t_(1_i)) to the instant, the ACK is received (t_(4_i)). This calculation is repeated for each FTM-ACK exchange, and the final RTT is the average over the successful number of FTM-ACK per burst. The estimated range can be obtained through Equation (2).

$$\text{Estimated Distance: } D_{est} = \frac{1}{2} * t_{RTT} * c \quad (2)$$

The precondition for a smartphone to support Wi-Fi RTT is that the Android Pie (or called Android P) operating system (OS) installed on it, which provides a number of APIs and allows a developer to add RTT methods in their own application. The application needs to declare the

ACCESS_FINE_LOCATION permission, and both location and Wi-Fi scanning need to be enabled on the end-user device [14].

One disadvantage of the Wi-Fi RTT so far is that it is hard to find many devices fully supporting the RTT protocol. The RTT-based ranging requires supports from both the ISTA and RSTA sides, which means all the devices must implement the 802.11mc standard (Android 2018). Although many smartphone manufacturers announced that their products support the RTT standard, e.g., the Essential, Nokia, OPPO, VIVO, Sony, and Xiaomi smartphones, none of them (except the Pixel phones) has successfully tested and recorded by researchers as a device supporting the Wi-Fi RTT protocol. From a simple test conducted by us, both OPPO Reno 5G and VIVO X27 are not supporting the Wi-Fi RTT (see Figure 2) and only the Pixel 3 phone supports the new protocol. For the RSTA devices, only the CompuLab WILD Wi-Fi RTT router was formally announced so far to support the Wi-Fi RTT protocol. However, a few Google APs were also successfully configured by us to do so.

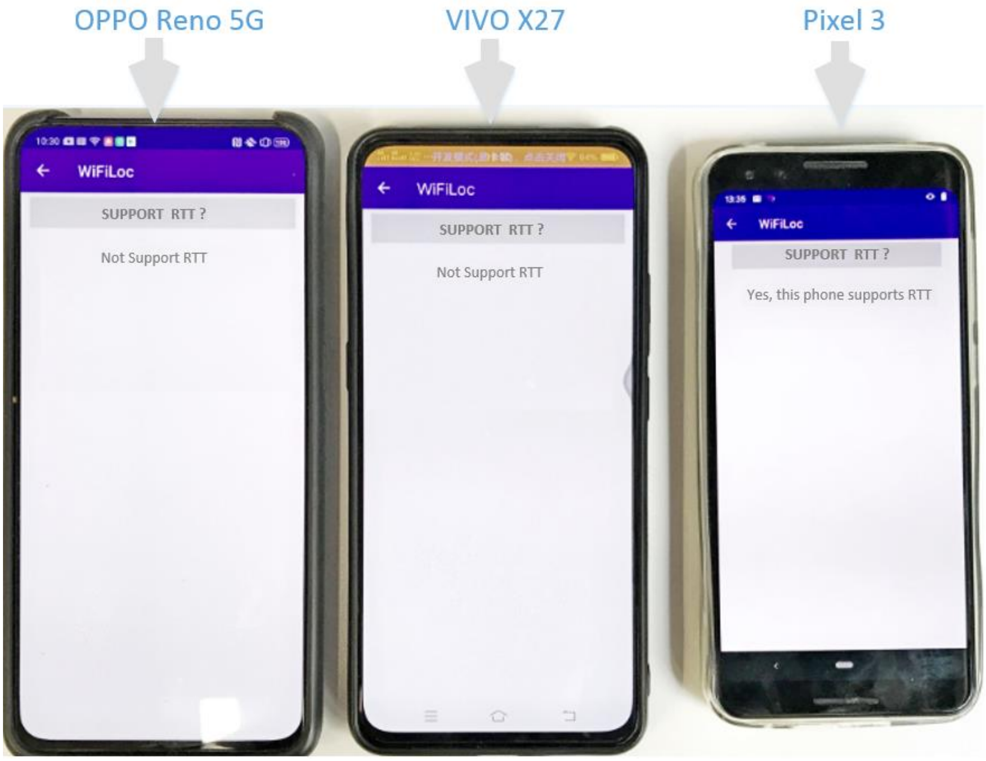


Figure 2. Results of Wi-Fi RTT supporting test from three different smartphones

3. METHODOLOGY

3.1 Conversions between different coordinate systems

A universal geographic coordinate system needs to be established for both positioning systems in order to compare the positioning accuracy between GPS and Wi-Fi RTT. Firstly, the east, north, up (ENU) Cartesian coordinate system is defined according to the vertical and horizontal dimensions from the latitudes and longitudes received, earth-fixed (ECEF, also known as earth-centred rotational (ECR)) coordinate system. The ENU coordinates are formed from a plane tangent to the Earth's surface fixed to a specific location and hence it is sometimes known as a local tangent or local geodetic plane (see Figure 3). The relationship between ENU and ECEF coordinate systems is shown in Figure 3.

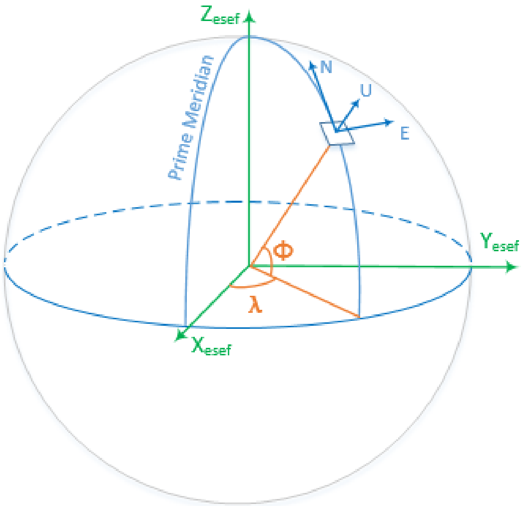


Figure 3. Relationships between the local ENU and the ECEF coordinate systems

A local coordinate system called $E'N'U'$ Cartesian coordinate system is also established based on the ENU coordinate system, and the only difference is that the $E'N'U'$system reset the values of E, N and U to 0 as a new initial point of the $E'N'U'$ system. Then, another local coordinate system is also established as the Wi-Fi localisation coordinate system. The Wi-Fi coordinate system (presented as X, Y and Z) is set to the same initial point with the $E'N'U'$system but with an angle (θ) as shown in Figure 4. In this case, let $Z = U'$, so only 2D coordinate systems are displayed.

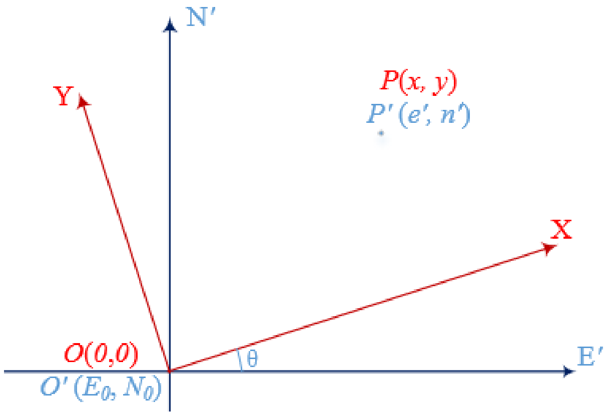


Figure 4. Relationship between the local $E'N'$ and *XY 2D* coordinate systems

Generally, the coordinates received by smartphones are geodetic coordinates. The comparison of the GPS estimates and Wi-Fi estimates require to convert the geodetic coordinates to ENU coordinates, then to the $E'N'U'$ coordinates, which is usually in a three-stage process:

1. Convert geodetic coordinates to $ECEF$ coordinates
2. Convert $ECEF$ coordinates to ENU coordinates
3. Convert ENU coordinates to $E'N'U'$coordinates

The above conversion processes can be summarized as:

$$(\phi, \lambda, h) => (X_{ecef}, Y_{ecef}, Z_{ecef})$$

$$=> (E,\ N,\ U)$$

$$=> (E',\ N',\ U')$$

In summary, a geodetic coordinate received from GPS is converted to a local coordinate system. Equation (04) is used for the conversion between ENU and $E'N'U'$ coordinates.

$$\begin{cases} E = E' + E_0 \\ N = N' + N_0 \end{cases} \tag{3}$$

Accuracies can be compared between $\begin{bmatrix} E' \\ N' \end{bmatrix}$s from the GPS and the positions from local Wi-Fi RTT.

3.2 Wi-Fi RTT-based positioning processes

Multilateration and simplified least squares (LS), for estimating the position from Wi-Fi RTT. The estimated distances from smartphones need to be calibrated using an experimental correction value, which can be obtained from an initial evaluation test.

Four APs with the strongest values of received signal strength indicator (RSSI) is selected for conducting the LS process if there are more than 4 APs connected.

Compared to the latitudes and longitudes received, the height values form GPS is less accurate; on the other hand, the height of the APs usually are constant values. Therefore, only 2D coordinates are concerned in this research. All 3D distance values are simplified to 2D values, which means only X and Y coordinates are considered for the multilateration process.

Assuming P(x, y) is the target position of a TP to be estimated. The exact formulas are:

$$d_i^2 = (x - x_i)^2 + (y - y_i)^2 \tag{4}$$

$$\text{or: } x^2 + y^2 - 2x_i x - 2y_i y = d_i^2 - x_i^2 - y_i^2 \tag{5}$$

Let $p = x^2 + y^2$, and

$$X = [p \quad x \quad y]^T$$

$$B = \begin{bmatrix} 1 & -2x_1 & -2y_1 \\ \vdots & \vdots & \vdots \\ 1 & -2x_n & -2y_n \end{bmatrix}$$

$$L = \begin{bmatrix} d_1^2 - x_1^2 - y_1^2 \\ \vdots \\ d_n^2 - x_n^2 - y_n^2 \end{bmatrix}$$

where: $i = 1, 2, \ldots, n$ and $n = 3 \ or \ 4$. X can be calculated by:

$$X = (B^T B)^{-1} B^T L \tag{6}$$

Finally, the coordinates of the point P(x, y) can be obtained from Equation (12).

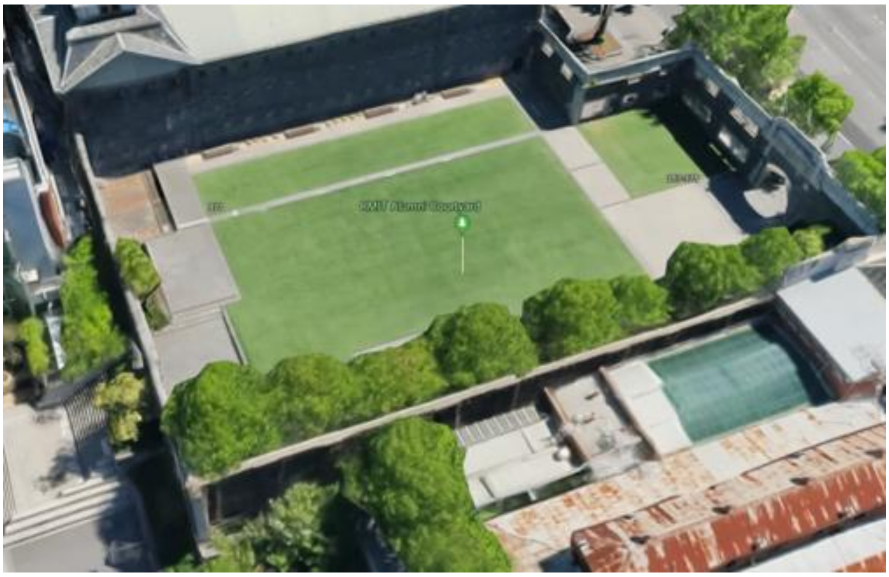
4. TEST & ANALYSIS

4.1Testbed establishment

As shown in Figure 5a, an area of about 30 x 25 m^2, located in the RMIT Alumni Courtyard behind the Old Gaol, was selected as the testing area. Twelve testing points (TPs) were marked on the ground, and the distances in X and Y directions to each adjacent points are all 6 metres as shown in Figure 5b. The 4 APs are placed in the same height level with the smartphone so that the height values for both the APs and the smartphone were omitted during the multilateration process. The coordinates of the 4 APs in the local XY coordinates are shown in Table 1.

AP number	AP_1	AP_2	AP_3	AP_4
X	5.00	2.50	19.00	21.00
Y	3.00	15.00	20.00	3.00

Table 1. Coordinates of the 4 APs



(a) Testing area: RMIT’s Alumni Courtyard behind the Old Gaol

(b) The 12 TPs and 4 APs located in the testing area
Figure 5. Testbed establishment in city campus of the RMIT University

The Leica GS18 receiver (see Figure 6), a high precision GNSS receiver, was firstly used for determining the coordinates of 4 base points (TPs 1, 3, 10 and 12) as their true coordinates, then other true coordinates of the 8 TPs and 4 APs were defined accordingly with the assistance of a total station and a tape.

Figure 6. Definition of the true coordinates for the 12 TPs

A Pixel 3 smartphone was used for collecting the data from GPS and the Wi-Fi APs. Two Android APPs called GPS coordinates and Wi-Fi RTT Scan (see Figure 7) were used respectively for collecting the latitude and longitude data and RTT data at each TP. Five pairs of data were collected at each TP, and the average values were used as the location estimation process. The time interval between any two adjacent collections is 2 seconds.

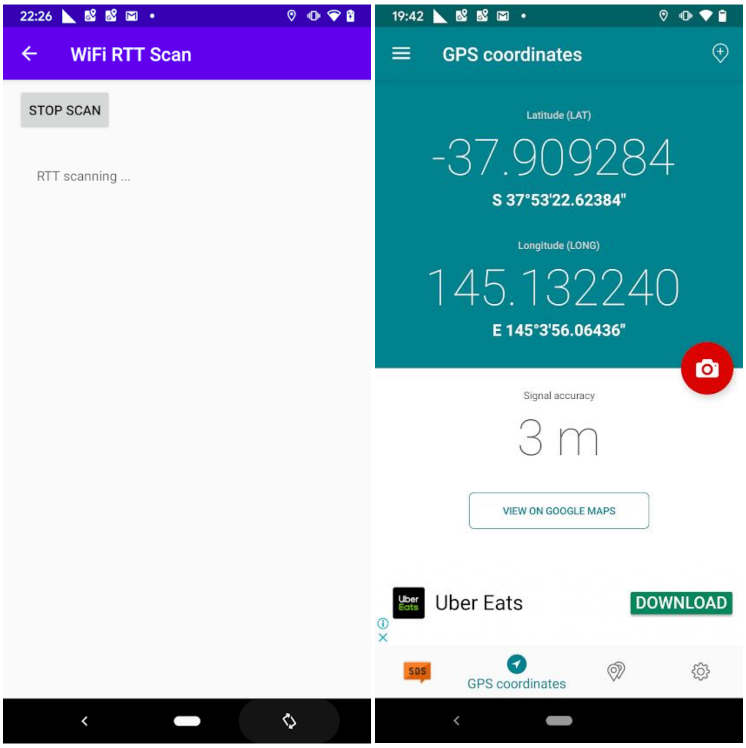


Figure 7. APPs used for colleting the GPS and Wi-Fi RTT data

4.2 Process and analysis of the received data

After the latitudes and longitudes of the 4 base TPs were obtained from the Leica GNSS receiver, the true coordinates of the other 8 TPs can be easily defined by transforming the local XY coordinates to EN coordinates with known bearing (i.e., θ, see Figure 4). In this research, θ is defined as -14.437°, calculated from the true coordinates of TP1 and TP12. The received latitudes and longitudes from the Android APP need to be converted to the grid coordinates for the accuracy comparison process later. All the data including the true EN coordinates received latitudes and longitudes, and the EN coordinates converted from the latitudes and longitudes, as well as the accuracies for the 12 TPs, are listed in Table2.

It is noticeable that all the accuracy values for the first 4 TPs are more than 11.917 m and then immediately reduced to the level of 1.824 to 7.226 m. The possible reason for this is that the GPS coordinates APP might not work in a stable mode at the beginning of 1.5 minutes or other disturbances, for example, the user had to stand by the smartphone for initial operation and the user’s body might partly block the GPS signals. Without consideration of the first four accuracy values, an average accuracy of 5.10 m was obtained from the rest 8 TPs for the GPS-based positioning, which is as the average level as expected. All these accuracy values are displayed in Table 2 and Figure 8.

TP No	True E (m)	True N (m)	Est. Lat	Est. Lon	Est. E	Est. N	Acc. (m)
P01	1378281.25	5768396.46	-37.80815	144.96520	1378288.00	5768379.90	17.888
P02	1378287.06	5768397.96	-37.80811	144.96526	1378293.74	5768384.24	15.263
P03	1378292.87	5768399.45	-37.80808	144.96524	1378292.22	5768387.55	11.917
P04	1378294.12	5768394.61	-37.80810	144.96512	1378281.38	5768386.47	15.116
P05	1378288.31	5768393.11	-37.80808	144.96524	1378292.22	5768387.55	6.803
P06	1378282.50	5768391.62	-37.80810	144.96512	1378281.38	5768386.47	5.270
P07	1378283.99	5768385.81	-37.80815	144.96516	1378284.32	5768380.52	5.299
P08	1378289.80	5768387.30	-37.80813	144.96521	1378288.97	5768382.27	5.101
P09	1378295.61	5768388.80	-37.80813	144.96527	1378294.28	5768381.70	7.226
P10	1378297.11	5768382.99	-37.80816	144.96531	1378297.45	5768377.98	5.023
P11	1378291.30	5768381.49	-37.80815	144.96523	1378290.50	5768379.85	1.824
P12	1378285.49	5768380.00	-37.80818	144.96514	1378282.19	5768377.37	4.218

Table 2. Process of the data received from GPS

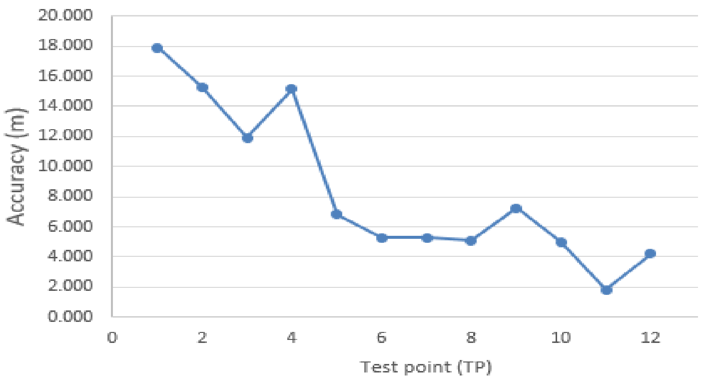


Figure 8. Positioning accuracies based on the data received from GPS

While collecting the data from GPS, Wi-Fi RTT ranging data were also collected in the same period. For each TP, the four ranging values received from the 4 APs need to be calibrated by adding a deviation correction value (i.e., -3.348 m) according to the research results from (Bai and Kealy 2019), then, they were applied to a multilateration process through Equations (10) to (12). The accuracy value for the TP was obtained based on its estimated local X and Y coordinates. The results and relevant data are displayed in Table 3 and Figure 9.

TP No	X	Y	Est. X	Est. Y	Acc. (m)
P01	6.00	20.00	5.05	20.71	1.191
P02	12.00	20.00	11.83	20.07	0.188
P03	18.00	20.00	15.80	20.92	2.383
P04	18.00	15.00	17.57	16.71	1.768
P05	12.00	15.00	10.22	15.86	1.979
P06	6.00	15.00	4.95	15.22	1.072
P07	6.00	9.00	5.94	8.82	0.190
P08	12.00	9.00	11.21	9.31	0.851
P09	18.00	9.00	17.92	11.10	2.102
P10	18.00	3.00	16.97	0.94	2.307
P11	12.00	3.00	11.91	1.27	1.735
P12	6.00	3.00	6.91	2.50	1.039
				Average:	1.40

Table 3. Process of the data received from the Wi-Fi APs

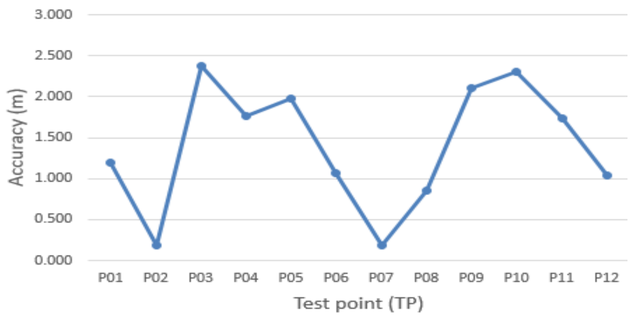


Figure 9. Positioning accuracies based on the data received from the Wi-Fi APs

There are still some issues that need to be considered for the above positioning estimation process. Apart from the unstable mode of the smartphone at the beginning of 1.5 minutes, other factors also exist to affect the positioning accuracies, such as multi-path effect, effects from the people walking around in the area during the test, and the smartphone user, who have to stand by the phone in a very near distance to operate the phone.

The abovementioned test results show that positioning with Wi-Fi RTT can obtain much better accuracy than with GPS. As Wi-Fi services are more and more common and free available in many world-wide cities, location-based service (LBS) with Wi-Fi applications will become more and more popular and vital for people’s daily activities.

3. CONCLUSIONS

This paper presents an evaluation and comparison study of GPS and Wi-Fi RTT based localisation using a smartphone as the end-user device. The experimental test was conducted in a relatively open area of the town centre in Melbourne. Relevant data from both GPS and Wi-Fi RTT are collected simultaneously from the same TPs, and other user environmental factors for both GPS and Wi-Fi are also the same. Results showed that the average accuracy for Wi-Fi RTT based localisation is 1.40 m and much better than the accuracy obtained from the GPS. This result is also firmly promising compared with the traditional way of Wi-Fi and smartphone-based localisation results.

Implementation and comparison of these technologies in a real-time kinematic mode will become the next step of our research plan.

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