Comparison of RSSI-Based Indoor Localization for Smart Buildings with Internet of Things

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***Abstract*—In many smart building applications, being able to accurately track targets is important to provide users with knowledge of their surroundings. This can enable robust and efficient workspaces to be developed which can be used to improve the lives of those who use them. Global Positioning System (GPS) has a simple implementation and accuracy up to five meters when it is used for outdoor system. However, being able to accurately and efficiently locate devices indoors has been a major challenge in smart buildings. Since GPS cannot be used indoors, there is a need for other wireless technologies which are capable of accurately tracking a target. In this paper, we compare three commonly used wireless technologies for indoor localization: Zigbee, Bluetooth Low Energy (BLE), and WiFi. The technologies are compared in terms of localization accuracy and power consumption. According to the experimental results, WiFi is the most optimal technology for use in an indoor localization system, followed by BLE. WiFi was found to be the most accurate and precise technology with an averaging error of 0.5183 m and variance of 0.0979 m. However, in terms of power consumption WiFi was the worst using 216.71 mW while BLE was the best only using 0.367 mW.**

***Keywords*— Zigbee; Bluetooth Low Energy; WiFi; Indoor Localization; Smart Buildings.**

I. Introduction

The Internet of Things (IoT) is advancing a new breed of smart buildings. Small devices such as wearables and beacons are communicating information and sensor data about their surroundings to central stations to increase the knowledge of their environment. In order to make use of the delivered information, having a centralized server know the location of a device is just as important as the data it receives. Without knowing the approximate location of a device, the information produced becomes useless and its energy reserves are wasted. Once a device knows its approximate location, it can share that information with the other devices in a smart building. When all of the devices in a smart building are aware of their approximate positions, being able to add, move, or remove devices becomes easier as the location information can be modified in real-time. Hence, localization is an important step towards developing smart buildings [1].

Localization is the process of determining the position of a device, using algorithms to calculate the position with the information that is available. Due to the small size of the majority of IoT devices, their hardware is often limited, hence, the amount of information available that can be used for localization is also limited. Most IoT devices contain low storage units and basic communication capabilities. In order for localization algorithms to be successful, they must be able to function once targets have been deployed utilizing the limited resources they contain.

A number of techniques exist for determining the location of a device, with the most common method involving a Global Navigation system such as the Global Positioning System (GPS) [2]. However, GPS is expensive to implement on a device, requiring an immense amount of energy to function, sacrificing the device run-time for a precise location. Moreover, a GPS receiver requires a Line-of-Sight (LoS) to satellites to function properly, therefore, for outdoor localization, GPS is able to provide an accurate position of a device. On the other hand, when near obstacles or inside a building, LoS to satellites is eliminated and GPS can no longer be used, hence, other localization techniques need to be applied. Hence, other technologies should be used for indoor localization and tracking systems.

Wireless technologies can alleviate the problem of indoor localization in smart buildings. Most of IoT devices have at least one wireless communication unit and participate in data communication. In this paper, through experimentation, a comparison between the accuracy and power consumption of Zigbee, Bluetooth Low Energy (BLE), and WiFi is performed for the design of an indoor localization system for smart buildings with IoT devices. The wireless technologies were selected based on their popularity among IoT devices. All tests performed were done using a trilateration technique where the RSSI values were used in determining the approximate distances between transmitting devices and a receiver.

The rest of this paper is organized as follows: the related work is reviewed in Section II, followed by the system description in Section III. The experimental methodology and setup are discussed in Section IV, along with the results and discussions in Section V. Section VI concludes this work.

II. Related Work

In recent years, RSSI-based trilateration has become one of the most utilized methods for performing localization due to its simplicity, low complexity, and high accuracy relative to GPS-based systems [3]. The system presented in [4] used RSSI and trilateration positioning based on Zigbee for the monitoring of mental patients in hospitals. The system proved to be a success, being able to improve the safety of the patients being tracked and could gather additional information that would not otherwise be known. Zigbee was considered ideal for the system as it provided a lower power consumption, higher accuracy, and farther monitoring range than other wireless technologies.

Another Zigbee-based system was discussed in [5], where trilateration tests were performed in both outdoor and indoor environments to determine how multipath effects would affect the accuracy. Results showed that outdoors, Zigbee achieved an accuracy below one meter. When indoors, results varied greatly with large errors occurring in the RSSI readings due to multipath effects. By performing tests first outdoors then indoors, a better model was found which was used in an attempt to more accurately relate RSSI values to distances.

In [6], a system using WiFi-based trilateration was presented. Results proved that when performing localization indoors due to interference in signals, errors can occur. It was found that the error could be reduced by using additional reference points to perform positioning estimation with greater accuracy. By then selecting reference points which are the most optimal in the calculation, a greater accuracy could be achieved since points with a lower resolution in the system could be ignored. In [7], a system using prototype nodes was developed using RSSI and trilateration with BLE beacons to perform localization. Results demonstrated that the system had an average accuracy of less than a meter, which was considered high when compared to other types of localization systems. The BLE beacons had low power requirements and were easy to deploy in multiple environments, while there are also solar powered beacons [8].

The system discussed in [9] used a custom developed Android application to compare WiFi access points and BLE beacons for performing localization utilizing RSSI with trilateration. Results demonstrated that WiFi had a much higher localization accuracy compared to BLE. BLE was shown to produce signal strengths that varied greatly over time. However, due to the low power consumption, and easy installability of the beacons, this made BLE a much simpler system to set up for localization. To improve the results, it was suggested that a greater number of WiFi access points be used to create additional signals that could be used for localization. In [10], the performance of BLE beacons for indoor localization in smart buildings was examined.

In this paper, we compare the wireless communication technologies Zigbee, BLE, and WiFi in-terms of accuracy and power consumption. For the comparison, prototype systems were designed in the testing of each of the technologies.

III. System Overview

This section introduces the system specifications, including the communication protocols, and hardware components used for each of the localization experiments. An overview of all transmitting devices used in the execution of the experiments performed can be seen in Fig. 1.

A. Zigbee

Being low in cost, energy efficient, and able to create mesh networks, Zigbee is a communication protocol based on the

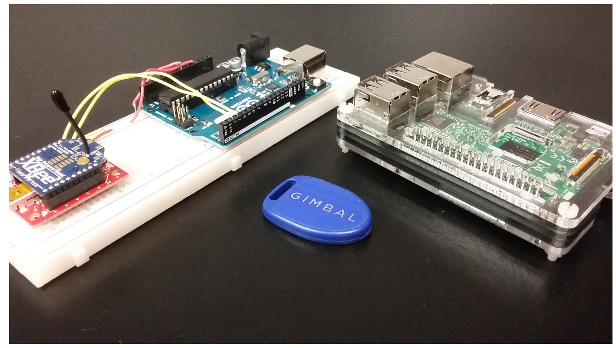


Fig. 1: Equipment used in setting up the experiments. From left to right: Arduino Uno with Series 2 2mW Wire XBee, Gimbal Series 10 Beacon, RaspBerry Pi 3 Model B.

IEEE 802.15.4 standard used in the creation of personal area networks with small antennas [11]. The 802.15.4 standard uses carrier-sense multiple access with collision avoidance (CSMA/CA) to control the flow of information through the network and prevent any loss of data. Best known for its simplicity and low-power usage, Zigbee provides secure networking capabilities, low data rates, and an increased network run-time.

In creating a Zigbee network, Series 2 2mW Wire Antenna XBees were used. Designed for high-throughput applications with low latency requirements, the XBee is an easy-to-use device that can quickly create multipoint Zigbee networks. Due to the limited processing power of the XBees themselves, a microcontroller was necessary to control the flow of information. The microcontroller selected was an Arduino Uno, due to its ease of integration with the XBee and low power requirements.

B. Bluetooth Low Energy

BLE focuses on ultra-low power consumption while maintaining a communication range similar to that of classic Bluetooth [12]. One type of device that has been created since the introduction of BLE technology is known as a beacon. BLE beacons are small, inexpensive, and fully wireless transmitting devices. They work by transmitting packets that implement either Apple's iBeacon [13] or Google's Eddystone [14] protocol structure.

For the BLE experiments, Gimbal series 10 Beacons were used as the transmitting devices. For the purposes of the experiments, the Gimbal beacons were configured with Apple's iBeacon protocol. The iBeacon packet structure defines three distinct fields. The first being the Universally Unique Identifier (UUID), a 16-byte field used to identify a set of beacons. The second and third fields are the Major and Minor values respectively. Both fields are 2 bytes wide and are commonly used to further differentiate individual beacons [13]. Each of these fields is configurable by the application developer for their own purposes.

In the experiments, each beacon was set up with a shared UUID and their own unique major and minor values. The

Wireless Technology	Range (m)
Zigbee	100
BLE	60
WiFi	70

TABLE I: Common transmission range of the wireless communication technologies.

receiving device was a Google Nexus 5 smartphone running Android 6.0.1. The Nexus 5 ran an open source Android application called *Beacon Scanner*. The application allowed for the reading of the raw RSSI values of any beacons that were in the vicinity.

C. WiFi

WiFi is a wireless technology commonly used in creating a Wireless Local Area Network (WLAN) [15]. To connect to a WLAN, a wireless access point is required. Due to security concerns when using WiFi, extra measures are required to protect users who are connected to the network. Taking extra precautions can often cause slower speeds compared to wired networks as needing to encrypt transmissions to prevent unwanted access from anyone who is within the range of the access point. Hence, WiFi has a much larger security concern than Zigbee and BLE due to its large data-transmission rate, and possible uses for the technology.

To create a WLAN using WiFi, a Raspberry Pi 3 Model B was used. The device contained an integrated WiFi antenna, hence, a simple WLAN could be created. To set up a WiFi experiment, the transmitters were configured to broadcast signals and the receiver set to continuously poll its WiFi antenna for any of the required signals.

D. Comparison Between Wireless Technologies

When comparing the differences between the wireless technologies, the transmission range is an important factor that needs to be considered. By utilizing a technology with a wider transmission range, fewer devices would be needed in order to cover the same area, hence, the cost of an implemented system would be reduced. The most common transmission ranges for the technologies being tested can be seen in Table I. Note, since the transmission range is limited by factors such as transmission power, antenna type, and location, the expected range can greatly differ based on the type of device that is used.

Based on the values found, Zigbee has the highest transmission range, capable of reaching distances up to 100 m. WiFi was the next highest, commonly transmitting 70 m in distance. Lastly, BLE had the lowest transmission range of all the technologies tested, being able to reach a distance of 60 m.

IV. Methodology and Experimental Setup

In this section, the methodology used to acquire location information from the different devices is described followed by the set up of the experiment.

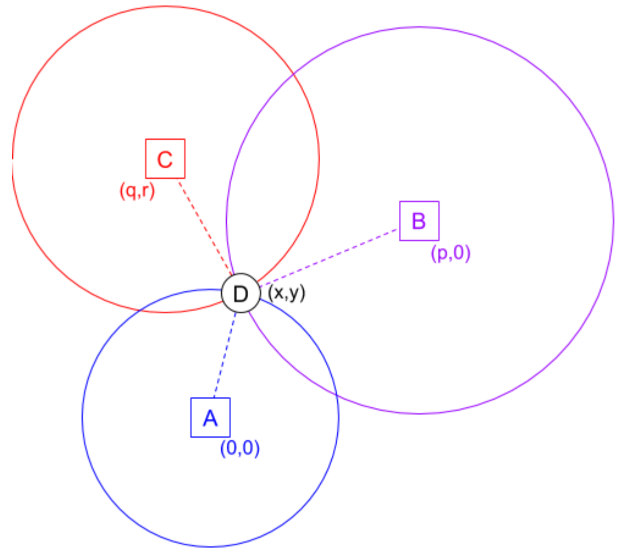


Fig. 2: Trilateration setup.

A. Methodology

To use trilateration in determining a position, four devices are required: three transmitters and a receiver. When calculating using trilateration, the locations of the transmitters and the distances from each of the transmitters to the receiver are required. The former requires manual measurements to determine and the latter uses RSSI measurements. By utilizing RSSI values from received signals along with the path-loss model [16], an approximate distance between the transmitters and the receiver could be found. For trilateration, a similar approach as in [3] was followed.

Figure 2 outlines the set up of the devices for calculating using trilateration. Nodes were placed according to the p, q, r, x, and y coordinates. p is the distance between nodes A and B along the x-axis. q and r are the distances between nodes A and C along the x and y-axes respectively. While x and y are the distances between nodes A and D along the x and y-axes respectively. Nodes were moved along these positions and the coordinates recorded.

B. Experimental Setup

In order to perform an accurate comparison between Zigbee, BLE, and WiFi when used for indoor localization, an equal set of tests was performed where minimal interference from the environment would affect the results. For testing purposes, a 5.6m by 5.9m meeting room, seen in Fig. 3, was used, which contained only tables and chairs. No people were located in the room while the experiment was conducted. Since RSSI values are prone to interference and it is impossible to remove all devices that could produce any noise, experiments were conducted in the evening to ensure that constant interference levels would be present which would affect all tests equally. During testing, nodes were placed on tables in order to simulate a height common to that of an individual carrying a smartphone in their pocket, or wearing a smart device.

Fig. 3: Experimental environment.

To perform equal tests, all of the transmitting devices were configured with a transmit power level of -10 dBm, and a transmit interval of 0.5 seconds. A transmit power of -10 dBm was chosen due to the XBees and beacons both containing a set list of levels that were customizable for the devices. Both devices contained -10 dBm as one of the configurable values, hence, would allow for an equal set of tests to be performed. The Raspberry Pi 3 did not suffer from the same limitations and could be programmed with a transmit power.

A transmit interval of 0.5 seconds was chosen due to it being one of the options that were customizable for the Gimbal Series 10 Beacons. When performing indoor localization, a real-time system requires a quick turnaround time, therefore, the faster the transmit time, the quicker the location information can be calculated and updated. If the system is too slow, objects would appear to jump positions in an environment which would not be ideal in a real-time localization system. Hence, 0.5 seconds was considered an ideal transmit interval. The other devices used were microcontrollers and did not suffer from the same limitations, therefore, a time of 0.5 seconds could be selected for all of the devices.

Due to the Arduino Unos and Raspberry Pis requiring an external power source to operate, USB cables were connected to wall outlets to provide power to the devices. The beacons did not suffer from the same issue as they used batteries.

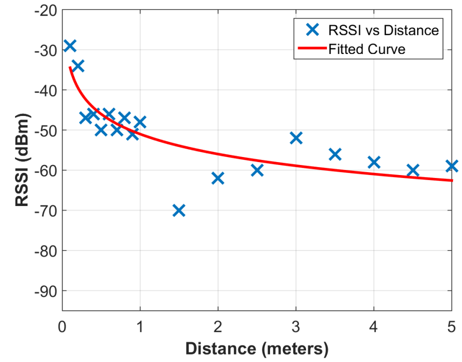
V. Experimental Results and Discussion

This section describes the path-loss model that was used, followed by the experimental results and a discussion of useful insights from the experiments.

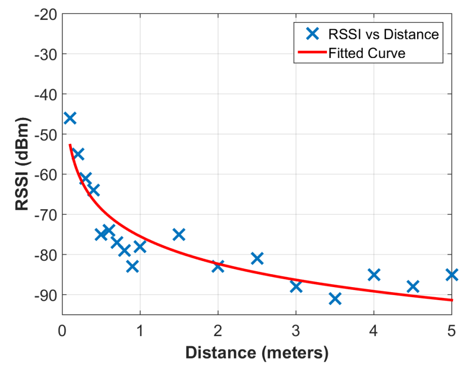
A. Path-loss Model

Before any experiments could be performed, the path-loss model for each of the systems needed to be obtained. The models created for each of the systems can be seen in Fig. 4 and the values found from the models for the path-loss exponent, n, constant, C, and coefficient of determination, R^2, can be seen in Table III.

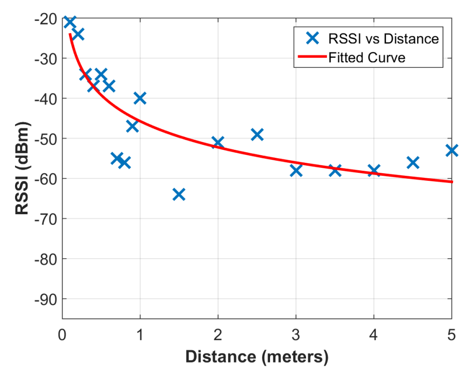
For each system, a single transmitter and receiver were placed in positions between 0 to 5 meters and the RSSI values recorded. Between 0 and 1 meter, nine points were taken, every 0.1 meters. Between 1 and 5 meters, another nine points were taken, every 0.5 meters. After all the values were found, the distance vs. RSSI was plotted, then using Matlab's curve fitting function, the path-loss model could be fitted to the data and a model determined.



(a) Zigbee.



(b) BLE.



(c) WiFi.

Fig. 4: Curve fitting models for the testing environment.

B. Experimental Results

In total, eleven experiments were performed for each of the systems to determine which had the highest accuracy based on the tests performed. In each of the tests, the location of all of the nodes was recorded along with the measured RSSI values

Transmitter Distances			Receiver Coordinates		Calculated Position Zigbee			Calculated Position BLE			Calculated Position WiFi		
p	***q***	***r***	***x***	***y***	***x***	***y***	***Error***	***x***	***y***	***Error***	***x***	***y***	***Error***
1	0	1	0.5	0.5	0.5560	0.5337	*0.0653*	2.7327	3.0481	*3.3879*	0.4822	0.4878	*0.0215*
1	0	2	0.5	0.5	0.6612	1.0000	*0.5253*	2.7983	1.9142	*2.6986*	0.4367	1.0071	*0.5110*
2	0	2	0.5	0.5	-0.2293	1.0211	*0.8963*	1.2697	1.6561	*1.3889*	0.9781	1.0220	*0.7078*
2	0	2	1	1	0.7630	-7.5356	*8.5389*	1.3379	1.3379	*0.4779*	0.9168	1.0099	*0.0838*
3	0	2	1	1	0.4148	-14.8432	*15.8540*	0.1642	1.4870	*0.9673*	1.4349	1.0083	*0.4350*
4	0	2	1	1	1.5660	-11.8926	*12.9050*	1.9180	1.3062	*0.9677*	1.8707	1.0038	*0.8707*
2	0	2	1	1	0.7039	-11.8926	*12.8960*	1.3062	1.2862	*0.4192*	0.6500	1.0197	*0.3505*
2	1	2	1	1	0.8463	-0.2485	*1.2579*	1.4502	1.0384	*0.4518*	0.9955	0.6989	*0.3011*
2	1	2	2	1	2.9936	1.6662	*1.1963*	1.6061	1.0219	*0.3945*	1.0387	0.7525	*0.9926*
2	1	2	1	0	0.9656	-2.2644	*2.2647*	1.0278	0.6646	*0.6652*	0.9938	0.7212	*0.7212*
2	1	1	1	0	0.9656	-0.0344	*0.0486*	1.3101	0.3101	*0.4386*	0.9938	-0.7061	*0.7061*

TABLE II: Positional results and associated errors (meters).

	Zigbee	**BLE**	**WiFi**
n	2.238	2.776	2.881
C	-53.83	-77.92	-49.19
$\mathbf{R^2}$	0.6915	0.8500	0.7177

TABLE III: Parameters used in determining distance using the path-loss model.

Wireless Technology	**Error**	**Variance**
Zigbee	5.1317	37.6659
BLE	1.1143	1.0301
WiFi	0.5183	0.0979

TABLE IV: Average error in position (meters).

from each of the corresponding transmitters. For each of the experiments performed, the actual and estimated positions of the receiver for each of the wireless technologies along with the error between them can be seen in Table II.

To evaluate the overall accuracy of each system, an average error was calculated between all tests performed. In addition to the overall accuracy, the variance of the results was also determined. The final results can be seen in Table IV.

Based on the results, WiFi using the Raspberry Pi 3s proved to be the most accurate system overall deviating from the actual receiver position by 0.5183 m on average. Tests not only showed that WiFi was the most accurate, but it was also the most precise, obtaining a low variance of 0.0979 m, producing results that were consistently within one meter of the receiver's location.

BLE was the second most accurate technology, deviating by 1.1143 m on average. From the results, it was determined that when the receiver was in close proximity to the transmitters, the system produced large errors. Once larger distances were created between the transmitters and receiver, the errors became much smaller and more manageable. The errors at the short distances are what cause the variance for BLE to be much higher than that of WiFi, even though for larger distances BLE performed much better than WiFi. Interestingly, even though BLE had a much higher R^2 value when modelling the path-loss to the data, WiFi prevailed, being able to measure RSSI values that were more realistic to the distances between the nodes.

Last was Zigbee, deviating on average by 5.1317 m. As determined by the results, Zigbee behaved opposite to BLE, producing accurate results at close distances and poor results when the nodes were further apart. This led to Zigbee achieving a very poor variance of 37.6659 m, concluding that Zigbee in addition to not being accurate, is not very precise in its calculations. Part of the error could be attributed to the path-loss model created. At 1.5 m, Zigbee produced large RSSI values that were not properly accounted for using the path-loss model. Hence, when 1.5 m distance was placed between the nodes, large errors occurred in the calculations. While WiFi also had an unexpectedly large RSSI reading at 1.5 m, there were additional points in the model that were also affected by the outcome of the calculations, reducing the overall error.

When measuring the power consumption of the devices, it was determined that the power consumed was consistent during all of the experiments performed. It was determined that the distance between the transmitter and receiver did not affect the power consumption, as a result never varied greatly and could be easily determined. The calculated power consumption values for the wireless technologies tested can be seen in Fig. 5. In measuring the power consumption, the transmit power for all the devices was set to -10 dBm and the transmit interval was 0.5 seconds. If a higher transmission power or faster transmission interval were used, the power consumption would increase.

Based on the values determined, WiFi consumes the largest amount of power, utilizing 216.71 mW on average. The next largest was found to be Zigbee, which consumed 78.8 mW of power. BLE was found to be the lowest out of all the technologies tested, consuming only 0.367 mW of power.

C. Discussion

The experimental results revealed useful insights. In terms of accuracy, WiFi was the most accurate and the most precise. However, it also consumed the largest amount of energy. While the system set up used in these experiments was expensive, in a real-world environment, WiFi access points already exist in most indoor locations which could be utilized in reducing the overall cost of the system. Based on the transmission range, WiFi could create interference in a large area depending on

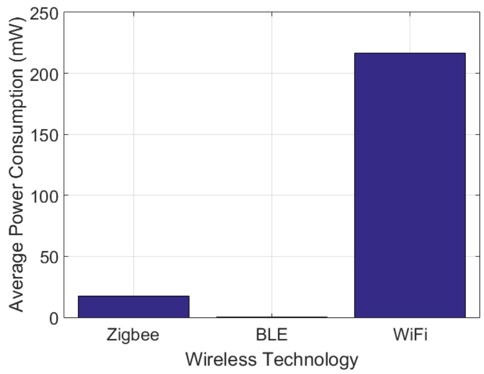


Fig. 5: Average power consumption of modules used.

the number of access points that are located in close proximity to each other.

On the other hand, BLE had a good accuracy and precision overall, where the energy consumption and cost are both low. While the transmission range is the smallest out of all the systems tested, a larger amount of devices would be needed to cover an area. Since the power usage of BLE devices is low, batteries could be used to power the devices which would make setting up the system simpler and more cost-effective than needing to redirect existing infrastructure in creating a localization system.

Finally, Zigbee had the worst performance in terms of accuracy but had the highest transmission range out of the technologies tested. It consumed more power than BLE, and it can be expensive requiring both a radio antenna and a microcontroller to function.

According to the experimental results, for an indoor localization system, BLE is a promising candidate. The other technologies had a much higher power consumption and would require the use of wired power supplies for the devices to function. BLE can function for large periods of time on a single battery charge and was designed for small range networks in the IoT era, hence, energy consumption was a priority. This was the main advantage of BLE technology that was also useful when it came to indoor localization systems.

VI. Conclusion

In this paper, we compared Zigbee, BLE, and WiFi for use in an indoor localization system. By using three transmitting devices, along with a receiver, trilateration could be performed to determine the approximate location of the receiver. Through experimentation, WiFi resulted as the most accurate system, on average deviating by 0.5183 m from the actual receiver position and the most precise with a variance of 0.0979 m. This was followed by the BLE deviating by 1.1143 m on average. BLE was also found to consume the lowest amount of power, utilizing 0.367 mW. In terms of transmission range, Zigbee can transmit the furthest distance of 100 m when LoS is available. Results demonstrated that for an indoor localization system WiFi is the most promising. Not only does it have the greatest accuracy, but due it being widely available can easily be implemented in an area. While the power consumption of WiFi is high, by utilizing routers that can provide internet access to users, localization can also be performed through the same system.

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