A Flexible and Scalable Localization System for Off-the-Shelf LoRa Devices

Honggang Zhao, Zuobin Liu, Gui Zhu, Chen Shi(✉), and Qingzheng Xu

College of Information and Communication, National University of Defense Technology, Xi'an, China
hgz_nwpu@163.com, 2551105254@qq.com, zhugui53@163.com, shishen26@163.com, xuqingzheng@hotmail.com

Abstract. Location Based Service is the key for most of IoT applications, and LoRa-based localization has attracted increasing research interests. The resolution of timestamp provided by LoRa gateway is still the determining factor for LoRa-based localization. Accurate localization is supported well with highly customized LoRa devices, meanwhile the current off-the-shelf LoRa devices have only microsecond accuracy. However, it's impracticable to use many hardware customized LoRa devices in real deployments, in which cost control must be taken into consideration. Therefore a flexible and scalable LoRa-Based localization system has been designed and implemented in this paper. It aims to easily and flexibly build the hardware platform by using off-the-shelf LoRa Devices. Its customized system server consists of LoRa-Network-Server, LoRa-Geo-Server and LoRa-App-Server. All the geolocation computation can be done in LoRa-Geo-Server, and results will be transported to LoRa-Network-Server. This makes the proposed system more scalable to develop specific LoRa-App-Server which will provide more Location Based Services. System test results in different Gateway deployments show that the system localization accuracy is basically within the accuracy range of "LoRaWAN Geolocation Whitepaper" presented by LoRa Alliance. It can provide a good experimental platform support for LoRa Localization technology research.

Keywords: Internet of Things · LoRa · Off-The-Shelf · Localization

1 Introduction

Low–Power Wide-Area Networks (LPWAN) are projected to support a major portion of the billions of devices forecasted for the Internet of Things (IoT) [1], in which Location Based Service is the key for most of applications (e.g., Car Parking [2], Elderly Assisting [3], Endangered Animals Protecting [7], Bus Positioning [14]). LoRaWAN is an open data link layer specification based on LoRa, and is designed from the bottom up to optimize LPWANs for battery lifetime, capacity, range, and cost. Also due to its signal's capability of propagating over long distances and penetrating many infrastructures, LoRa-based localization has attracted increasing research interests. As described in "LoRaWAN Geolocation Whitepaper" presented by LoRa

B. Li et al. (Eds.): IoTaaS 2020, LNICST 346, pp. 347–359, 2021.
https://doi.org/10.1007/978-3-030-67514-1_28

Alliance™ Strategy Committee, LoRa-based localization approaches can be divided into two classes: Received Signal Strength Indication (RSSI) based, for coarse positioning and Time Difference of Arrival (TDOA) based, for finer accuracy [4]. And this paper will study Localization System of TDOA-based approaches.

Fargas et al. [3] designed and implemented a tracking system in order to present accuracy results using LoRa technology. Carvalho et al. [8] designed a LoRa-based test system to study the feasibility of mobile sensing and tracking applications. Podevijn et al. [11] implemented an TDOA-based Localization system to investigate the performance of LoRa geolocation for outdoor tracking. However, because a radio signal translates to around 300 m in 1 μs and the timing resolutions of current off-the-shelf LoRa Gateways have only microsecond accuracy, the above three approaches have poor localization performance when implemented on off-the-shelf LoRa devices. Rajalakshmi et al. [12] designed a multi-band backscatter device which is sub-centimeter sized. Although the study of Rajalakshmi et al. achieves meter-level localization accuracy, the LoRa devices in their study need to be highly customized [13].

Some signal processing approaches have also been studied to improve the localization accuracy. Wolf et al. [6] proposed a multi-channel approach to enable precise ranging for LPWAN radio devices, in which oscillator frequency offsets and multipath influence were also taken into account. Bakkali et al. [5] presented an Extended Kalman Filter based approach to achieve the acceptable level of accuracy, in which particular attention is paid to the processing of outliers. However, it's generally difficult to effectively mitigate the effect of propagation environment and multipath, because it is hard to build an effective path-loss model when the signal propagating across different infrastructures and barriers. Besides, good accuracy results were obtained in literature [9], in which 42 gateways were used in hexagonal layout to improve the results and the signal from the end-node was received by at least 10 gateways. But this will require too much cost of network deployment.

According to the above studies, the resolution of timestamp provided by LoRa gateway determines the accuracy of LoRa-Based localization system. Obviously, the timing resolution of current off-the-shelf LoRa products is not sufficient for implementing accurate localization [10]. It is also impracticable to highly customize hardware of current off-the-shelf LoRa devices, which are originally designed to deployed in low cost scenarios.

So we aim to propose a design of LoRa-based localization system for off-the-shelf devices, with flexible, easy deployment capability and good scalability:

- The system will be designed for off-the-shelf LoRa devices, which means it's easy to build the hardware platform. And system servers will be deployed in Alibaba Cloud [15], which means it's flexible to adjust the servers' configurations.
- A new system server architecture will be proposed based on the ChirpStack [16]. All the geolocation computation can be done in LoRa-Geo-Server component, and results will be transported to LoRa-Network-Server component. This makes the proposed system more scalable to develop specific LoRa-App-Server component which will provide more Location Based Services.

- The TDOA extraction method will be proposed. And the end device's position can be estimated with CHAN algorithm [17]. System test results will be presented to show that it can provide a good experimental platform support for LoRa Localization technology research.

The remainder of this paper is organized as follows. Section 2 presents the proposed system architecture and the detailed design of system server. Section 3 describes how to extract TDOA and to determine End-Device's position in the LoRa-Geo-Server. Section 4 presents the system tests results using off-the-shelf LoRa devices. Section 5 concludes this paper.

2 System Design

The system consists of three parts: LoRa End-Device, LoRa Gateways, and System Server, in which the System Server is comprised mainly of LoRa-Network-Server, LoRa-Geo-Server and LoRa-App-Server. The system infrastructure is illustrated in Fig. 1, wherein the Gateways have only microsecond accuracy. Uplink transmissions from the LoRa End-Device are received and accurately time-stamped by LoRa Gateways, then synchronized LoRa Gateways forward these timestamps to the System Server as part of a frame's metadata, which also includes signal level, signal-to-noise ratio, frequency error, etc. Since a GPS receiver is embedded in the Gateway, the GPS coordinates are transmitted to the System Server by the Gateway periodically.

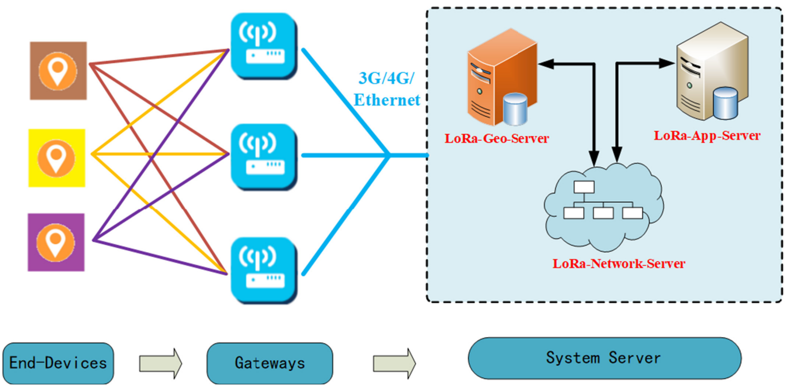

Fig. 1. System infrastructure

The new system server architecture is proposed based on the ChirpStack, and its architecture is illustrated in Fig. 2. The LoRa-Network-Server consists of two components: LoRa Gateway Bridge and LoRa Server, in which the LoRa Server has been highly customized:

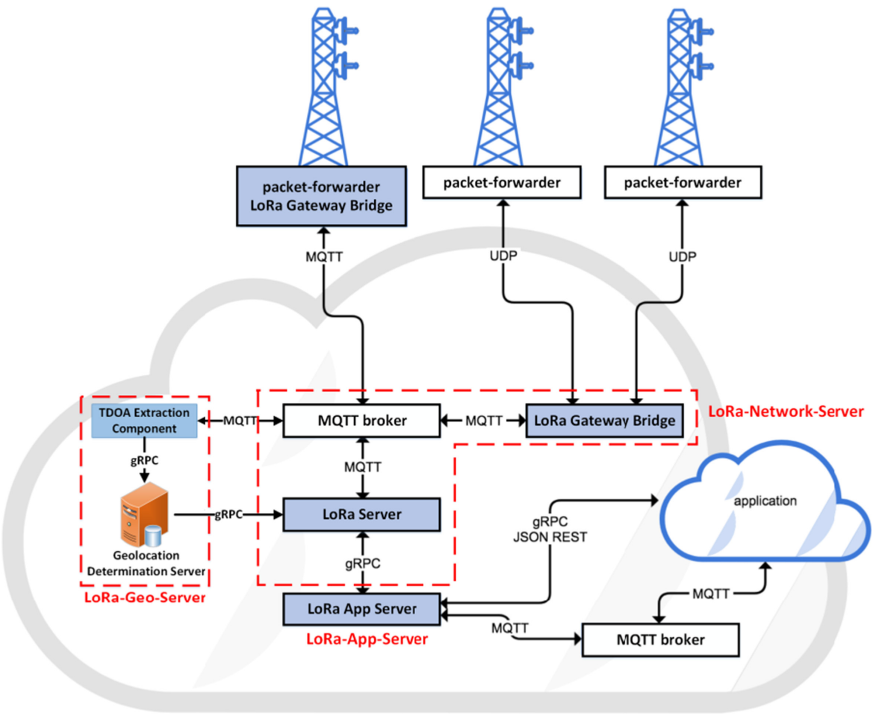

Fig. 2. System server architecture

- The LoRa Gateway Bridge component is responsible for the communication with Gateway. It also transforms the packet-forwarder UDP protocol into message over MQTT, and the messages are then forwarded to LoRa Server component.
- LoRa Server is responsible for managing the state of the network. It also de-duplicate data received by multiple gateways and forward it once to the LoRa-App-Server. In contrast to the current ChirpStack, it will receive the information provided by LoRa-Geo-Server, and no longer subscribe to MQTT topic(s) about localization.

The LoRa-Geo-Server consists of two components: TDOA Extraction Component and Geolocation Determination Server:

- TDOA Extraction Component receives all the events about localization from gateways, by subscribing to corresponding MQTT topic(s). Then TDOAs will be computed and forwarded to Geolocation Determination Server along with Gateways' coordinates, End-Device's short address, etc.
- Geolocation Determination Server will compute the End-Device's position, and transport it to LoRa Server.

The LoRa-App-Server will provide more powerful web-interface and APIs for management of users, organizations, applications, gateways and devices, because End-Device's position can now be provided by LoRa Server. That's to say more Location Based Services can be provided by the LoRa-App-Server.

3 Geolocation Computation in LoRa-Geo-Server

The Geolocation Computation consists of two phases: TDOA Extraction and Geolocation Determination, which are implemented in TDOA Extraction Component and Geolocation Determination Server respectively.

3.1 TDOA Extraction Component

TDOA Extraction Component is implemented in Java, and the detailed TDOA extraction process is illustrated in Fig. 3.

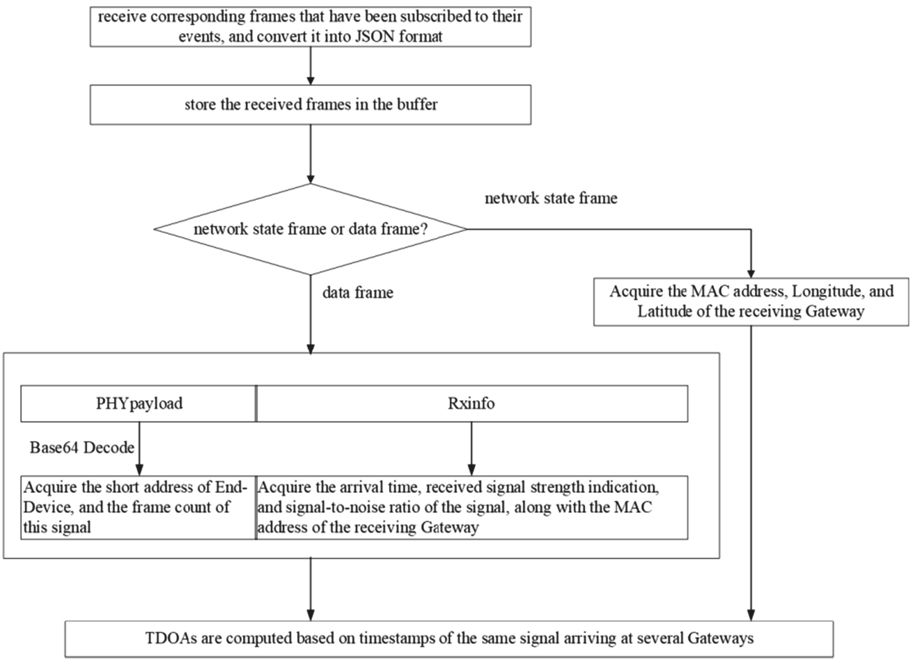

Fig. 3. TDOA extraction FlowChart

Firstly, it will receive all the events about localization by subscribing to its MQTT topic(s). Secondly, necessary information will be acquired, which includes Gateways' MAC addresses, timestamps of one signal arriving at several Gateways, Received Signal Strength Indication, signal-to-noise ratio, Gateways' longitudes, Gateways' latitudes, End-Devices' short addresses, Counts of signals from the End-Devices. Finally, TDOAs are computed based on timestamps of the same signal arriving at several Gateways.

3.2 Geolocation Determination Server

CHAN [17] algorithm will be implemented in Geolocation Determination Server. When TDOAs are acquired, the end-device can be placed on several hyperbolae. Then the end-device can be localized at the intersection of these hyperbolae. This is illustrated in Fig. 4.

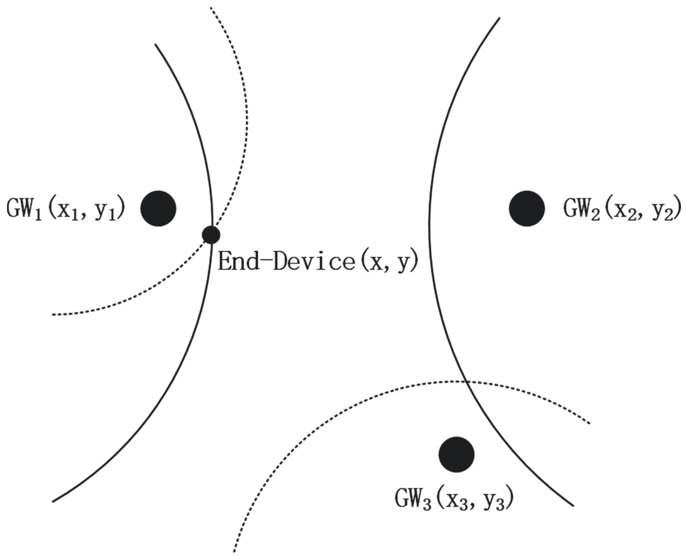

Fig. 4. Localization in CHAN algorithm

As shown in Fig. 4, the distance between End-Device and GW_i is given by Eq. (1), where $i \in \{1, 2, 3\}$.

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{1}$$

The distance between GW_i and GW_1 is given by Eq. (2), where $i \in \{2, 3\}$, $C = 3 * 10^8 m/s$, $t_{i,1}$ represents the time difference of the same signal arriving at GW_i and GW_1.

$$r_{i,1} = r_i - r_1 = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_1 - x)^2 + (y_1 - y)^2} = t_{i,1} * C \tag{2}$$

Then we can conclude Eq. (3) from Eq. (1) and Eq. (2), where $K_i = x_i^2 + y_i^2$.

$$\begin{cases} r_{2,1}^2 + 2r_{2,1}r_1 = (K_2 - K_1) - 2x_{2,1}x - 2y_{2,1}y \\ r_{3,1}^2 + 2r_{3,1}r_1 = (K_3 - K_1) - 2x_{3,1}x - 2y_{3,1}y \end{cases} \quad (3)$$

Given r_1 is known, the Eq. (3) can be transformed into Eq. (4):

$$\begin{cases} x = p_1 + q_1 r_1 \\ y = p_2 + q_2 r_1 \end{cases} \quad (4)$$

And p_1, q_1, p_2, q_2 in Eq. (4) are represented as follows:

$$p_1 = \frac{y_{2,1}r_{3,1}^2 - y_{3,1}r_{2,1}^2 + y_{3,1}(K_2 - K_1) - y_{2,1}(K_2 - K_1)}{2\left(x_{2,1}y_{3,1} - x_{3,1}y_{2,1}\right)},$$
$$q_1 = \frac{y_{2,1}r_{3,1} - y_{3,1}r_{2,1}}{x_{2,1}y_{3,1} - x_{3,1}y_{2,1}},$$
$$p_2 = \frac{x_{2,1}r_{3,1}^2 - x_{3,1}r_{2,1}^2 + x_{3,1}(K_2 - K_1) - x_{2,1}(K_2 - K_1)}{2\left(x_{3,1}y_{2,1} - x_{2,1}y_{3,1}\right)},$$
$$q_2 = \frac{x_{2,1}r_{3,1} - x_{3,1}r_{2,1}}{x_{3,1}y_{2,1} - x_{2,1}y_{3,1}}.$$

Then we can conclude Eq. (5) from Eq. (4) and Eq. (1):

$$\mathrm{a}r_1^2 + br_1 + c = 0 \quad (5)$$

And a, b, c in Eq. (5) are represented as follows: $\mathrm{a} = q_1^2 + q_2^2 - 1$, $\mathrm{b} = -2[q_1(x_1 - p_1) + q_2(y_1 - p_2)]$, $\mathrm{c} = (x_1 - p_1)^2 - (y_1 - p_2)^2$.

The r_1 can be obtained by solving Eq. (5). Then by substituting the value of r_1 into Eq. (4), the End-Device's coordinate (x, y) can be obtained.

Through the above steps, the End-Device can be localized when the same signal is received by 3 gateways. And when the End-Device's signal is received by more than 3 gateways, Eq. (6) can be established where $\mathrm{M} \geq 4$.

$$\begin{cases} r_{2,1}^2 + 2r_{2,1}r_1 = (K_2 - K_1) - 2x_{2,1}x - 2y_{2,1}y \\ r_{3,1}^2 + 2r_{3,1}r_1 = (K_3 - K_1) - 2x_{3,1}x - 2y_{3,1}y \\ \vdots \\ r_{M,1}^2 + 2r_{M,1}r_1 = (K_M - K_1) - 2x_{M,1}x - 2y_{M,1}y \end{cases} \quad (6)$$

Because the number of equations is greater than the number of unknowns, the least-squares method will be used. Then the End-Device's coordinate (x, y) can be obtained.

4 System Tests in Different Gateway Deployments

This section investigates the performance of the proposed localization system. Several tests have been carried out in different Gateway deployments, to present accuracy results using off-the-shelf LoRa devices.

4.1 Test in Gateway Deployment Case 1

The system is firstly tested in Gateway deployment case 1, which has 3 gateways. Figure 5 illustrates Gateways' and End-Device's geographic positions in the rural area. Figure 6 illustrates the test infrastructure, where the system server has been deployed on Alibaba Cloud [15]. Gateways are connected to the Internet through 4G LTE network. When Gateways receive signals from End-Device, they forward signals to the system server. Each Gateway is placed on a bench, and the antenna of each Gateway is about 1.5 m high.

In Gateway deployment case 1, the tests are carried out 100 times. The detailed localization errors are shown in Fig. 7, the mean localization error is 189.9465 m and the standard deviation is 94.9179 m. Figure 8 shows the estimated positions of End-Device, as well as the real positions of End-Device and Gateways. This verifies that the system localization accuracy is within the accuracy range of "LoRaWAN Geolocation Whitepaper" presented by LoRa Alliance [4].

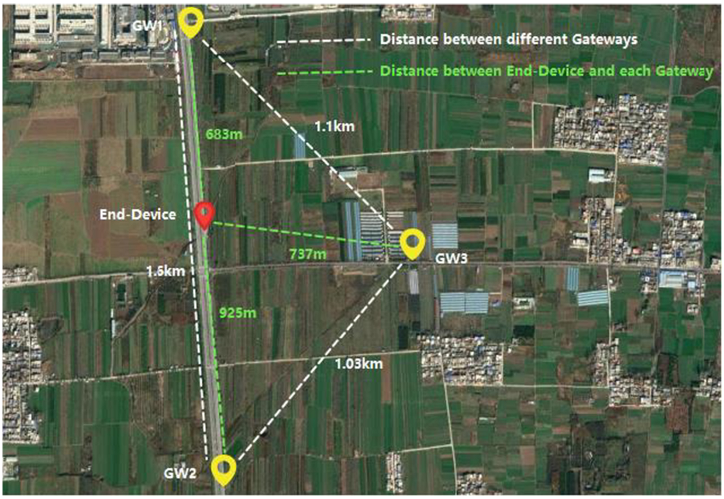

Fig. 5. Gateway deployment case 1

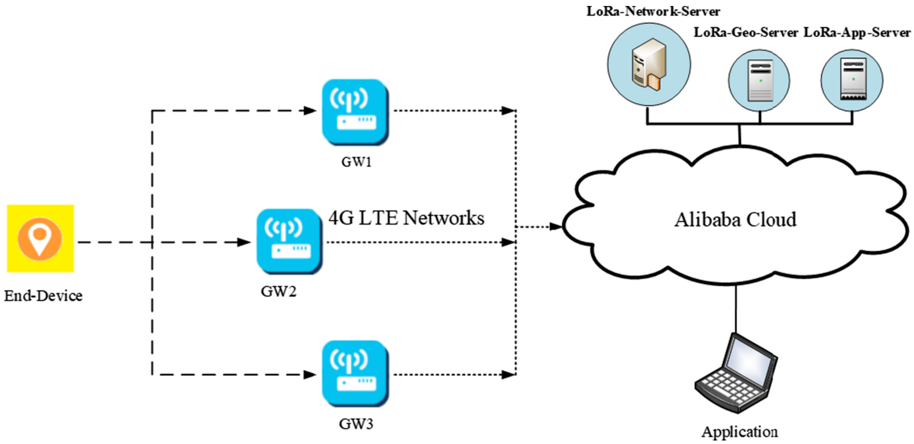

Fig. 6. Test infrastructure

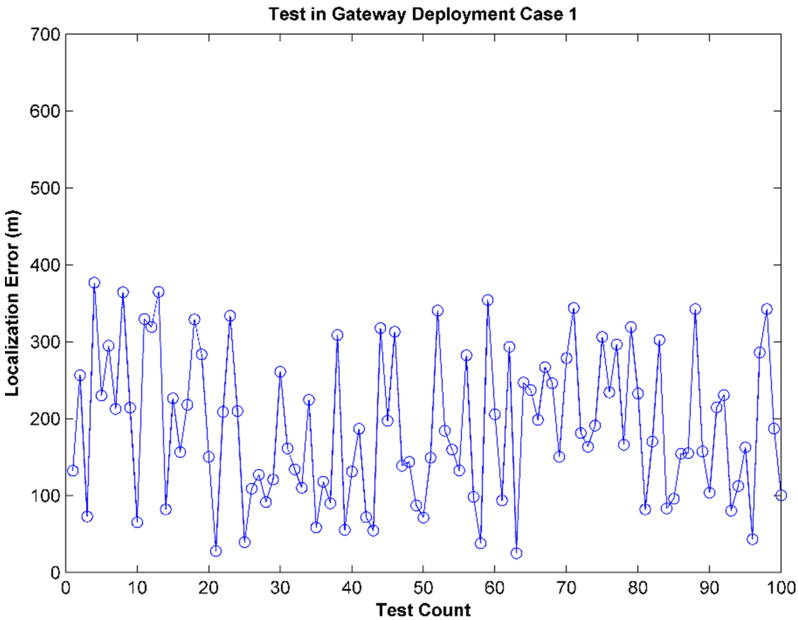

Fig. 7. Localization errors in gateway deployment case 1

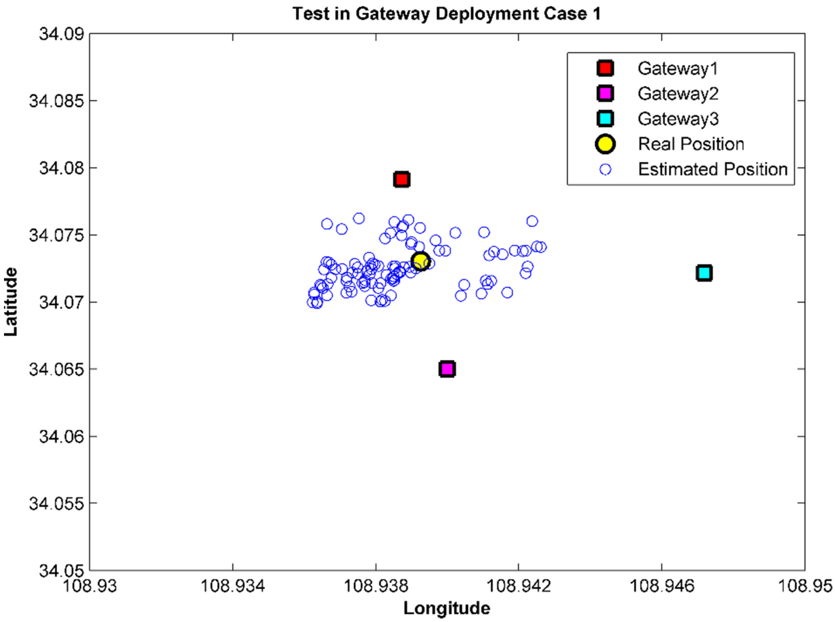

Fig. 8. Estimated positions of End-Device in gateway deployment case 1

4.2 Test in Gateway Deployment Case 2

The system is also tested in Gateway deployment case 2, which has 4 Gateways. In case 2 as shown in Fig. 9, Gateway 4 is added at the basis of case 1, and the End-Device is deployed 150 m north of the intersection of two roads. Each Gateway is placed on a bench, and the antenna of each Gateway is about 1.5 m high.

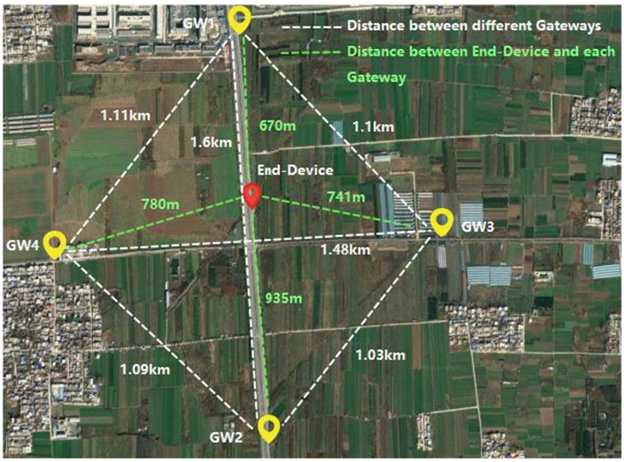

Fig. 9. Gateway deployment case 2

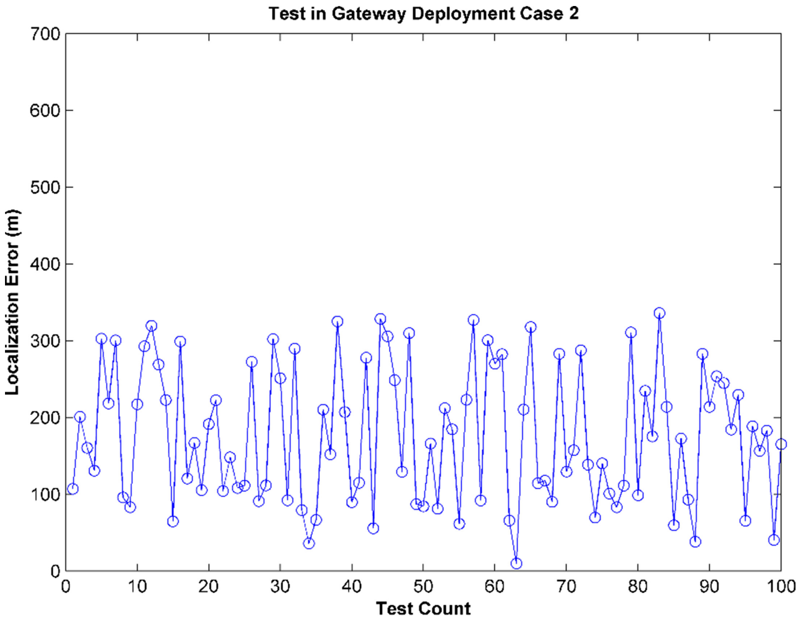

Fig. 10. Localization errors in gateway deployment case 2

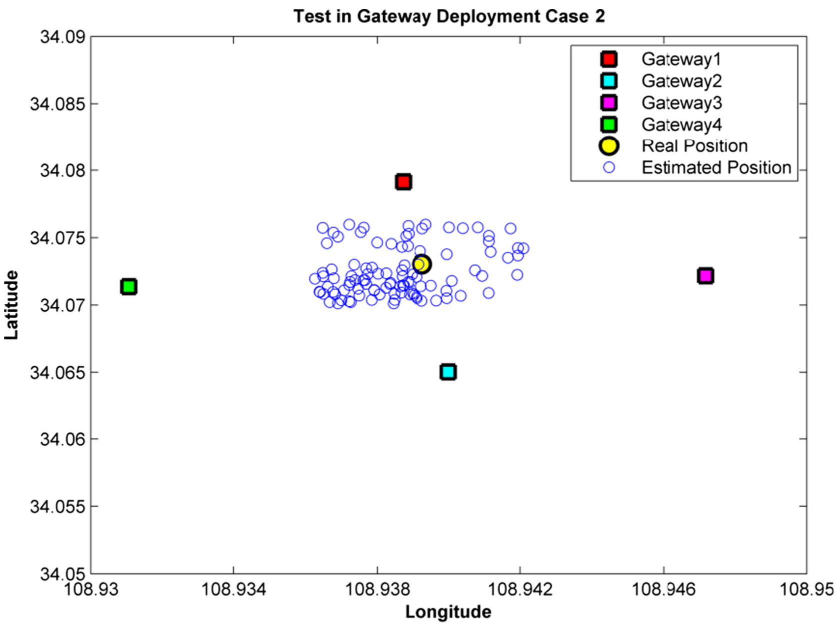

Fig. 11. Estimated positions of End-Device in gateway deployment case 2

In case 2, test infrastructure is similar to case 1 and system server is also deployed on Alibaba Cloud. The tests are also carried out 100 times. The detailed localization errors are shown in Fig. 10, the mean localization error is 176.35785 m and the standard deviation is 88.2780 m. Figure 11 shows the estimated positions of End-Device, as well as the real positions of End-Device and Gateways. We can see that the mean system localization error and standard deviation in case 2 are much less than in case 1. This is because that the number of Gateways is increased, four Gateways are deployed almost squarely and the End-Device is located almost in the center of four Gateways. In other words, the system localization accuracy can be improved with the improved Gateway Deployment. Besides, the deployment case of Port of Barcelona, presented in “LoRaWAN Geolocation Whitepaper” [4], has the similar open environment that case 1 and case 2 have. And in the deployment case of Port of Barcelona, the Gateways’ antennas are deployed directly on the rooftops of three-story metallic buildings. By contrast, the height of each Gateway’s antenna in case 1and case 2 is much lower. This is the main factor that the system localization accuracy in case 1and case 2 is not good as in case of Port of Barcelona. And because the system localization accuracy in case 1 and case 2 is still within the accuracy range of “LoRaWAN Geolocation Whitepaper” [4], it is proved that the proposed system would be a good experimental platform support for LoRa Localization technology research.

5 Conclusions and Future Work

In this paper, a flexible and scalable LoRa-Based localization system has been designed and implemented. Off-the-shelf LoRaWAN Node and LoRaWAN Gateways are respectively used as the End-Device and Gateways, wherein the Gateways have only microsecond accuracy. This means it’s easy and flexible to build the system hardware platform. The system server is customized based on ChirpStack. All the geolocation computation can be done in LoRa-Geo-Server, and results will be transported to LoRa-Network-Server. This makes the proposed system more scalable to develop specific LoRa-App-Server which will provide more Location Based Services. System test results in different Gateway deployments show that the system localization accuracy is within the accuracy range of “LoRaWAN Geolocation Whitepaper” presented by LoRa Alliance. It can provide a good experimental platform support for LoRa Localization technology research.

In the future, we’ll propose effective algorithms for specific scenario cases to mitigate the effect of propagation environment and multipath. Customized LoRa-App-Server will be also developed. And they’ll be both integrated into the proposed system in this paper.

References

1. Alliance, L.: A technical overview of LoRa and LoRaWAN. White Paper, November 20 (2015)
2. Gotthard, P., Jankech, T.: Low-cost car park localization using rssi in supervised lora mesh networks. In: 15th Workshop on Positioning, Navigation and Communications (WPNC), pp. 1–6. IEEE (2018)
3. Fargas, B.C., Petersen, M.N.: GPS-free geolocation using LoRa in low-power WANs. In: 2017 Global Internet of Things Summit (Giots), pp. 1–6. IEEE, Geneva (2017)
4. Lora Alliance Strategy Committee, et al.: LoRaWAN Geolocation White-paper. LoRa Alliance, January 2018
5. Bakkali, W., Kieffer, M., Lalam, M., et al.: Kalman filter-based localization for Internet of Things LoRaWAN™ end points. In: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1–6, IEEE, Montreal (2017)
6. Wolf, F., Villien, C., De Rivaz, S., et al.: Improved multi-channel ranging precision bound for narrowband LPWAN in multipath scenarios. In: 2018 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6. IEEE, Barcelona (2018)
7. Martin, B.: Technology to the Rescue. In: Survival or Extinction?, pp. 319–330. Springer, Cham (2019)
8. Carvalho, D.F., Depari, A., Ferrari, P., et al.: On the feasibility of mobile sensing and tracking applications based on LPWAN. In: 2018 IEEE Sensors Applications Symposium (SAS), pp. 1–6, IEEE (2018)
9. Lestable, T., Lalam, M., Grau, M.: Location-Enabled LoRa IoT Network:'Geo-LoRa-ting' your assets. Presentation, September (2015)
10. Dongare, A., Hesling, C., Bhatia, K., et al.: OpenChirp: A low-power wide-area networking architecture. In: IEEE International Conference on Pervasive Computing & Communications Workshops, pp. 569–574. IEEE (2017)
11. Nico, P., David, P., Jens, T., et al.: TDoA-Based Outdoor Positioning with Tracking Algorithm in a Public LoRa Network. Wireless Communications and Mobile Computing **2018**, 1–9 (2018)
12. Nandakumar, R., Iyer, V., Gollakota, S., et al.: 3D localization for sub-centimeter sized devices. In: Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems (SenSys'18), pp. 108–119. ACM (2018)
13. Gu, C., Jiang, L., Tan, R., et al.: LoRa-Based Localization: Opportunities and Challenges. arXiv: Networking and Internet Architecture (2018)
14. Guan, P., Zhang, Z., Wei, L., et al.: A real-time bus positioning system based on LoRa technology. In: 2018 2nd International Conference on Smart Grid and Smart Cities (ICSGSC), pp. 45–48, IEEE (2018)
15. Alibaba Cloud Homepage. https://www.alibabacloud.com/. Accessed 12 Feb 2020
16. ChirpStack Homepage. https://www.chirpstack.io/. Accessed 12 Feb 2020
17. Ma, L.: Research and application of wireless sensor location algorithm based on TDOA. Shandong University (2012)