

On-Demand Indoor Location-based Service using Ad-Hoc Wireless Positioning Network

Shigemi Ishida*, Shigeaki Tagashira†, Yutaka Arakawa‡, Akira Fukuda*

*Graduate School/Faculty of Information Science and Electrical Engineering, Kyushu University, Japan

†Faculty of Informatics, Kansai University, Japan

‡Graduate School of Information Science, Nara Institute of Science and Technology, Japan

Abstract—WiFi-based localization is a promising candidate for indoor localization because the localization systems can be implemented on WiFi devices widely used today. In this paper, we present a distributed localization system to realize on-demand location-based services. We define characteristics of on-demand from both the service providers' and users' perspectives. From the service providers' perspective, we utilize our previous work, a WiFi ad-hoc wireless positioning network (AWPN). From the users' perspective, we address two challenges: the elimination of a user-application installation process and a reduction in network traffic. We design a localization system using the AWPN and provide a location-based service as a Web service, which allows the use of Web browsers. The proposed localization system is built on WiFi access points and distributes network traffic over the network. We describe the design and implementation and include a design analysis of the proposed localization system. Experimental evaluations confirm that the proposed localization system can localize a user device within 220 milliseconds. We also perform simulations and demonstrate that the proposed localization system reduces network traffic by approximately 24 % compared to a centralized localization system.

Index Terms—on-demand, indoor localization, location-based Web service, ad-hoc wireless positioning network, WiFi mesh network

I. INTRODUCTION

Indoor localization is required to extend location-based services to indoor environments. Numerous localization approaches using technologies such as ultrasound, infrared light, and WiFi signals have been developed. In particular, WiFi localization technology is gaining importance in terms of deployment cost because it can be implemented on existing WiFi devices resulting in significantly reduced deployment cost.

Our goal is to implement on-demand indoor location-based services using WiFi localization technology. We define the characteristics of on-demand services from two perspectives.

- 1) *Service providers' perspective*: service providers can easily and instantly build a localization system anytime anywhere to provide a location-based service.
- 2) *Users' perspective*: users can use the service immediately, anytime, without installing a user application.

These on-demand characteristics are important for one-time use scenarios. Navigation in an exhibition event, for example, requires the on-demand characteristics because exhibitions exist typically for only a limited number of days and visitors use the system for only one day. Current indoor location-based services require a user application and the installation of WiFi access points (APs) in the environment, which inevitably restricts their applications to continuous-use scenarios.

To provide the on-demand characteristics from the service providers' perspective, we can employ previous work on WiFi localization. There are numerous proposals on WiFi localization [1–24]; some of these have addressed the reduction of deployment cost as a primary concern. These works direct us towards easily and instantly implementing a localization system. We have also developed a WiFi ad-hoc wireless positioning network (AWPN) for this purpose [25]. AWPN is a localization system built on a WiFi mesh network. Using AWPN, we can implement a localization infrastructure by simply installing WiFi APs and a localization server.

However, none of the previous works provide the on-demand characteristics from both the service providers' and users' perspectives simultaneously. To realize the on-demand characteristics from the users' perspective using our AWPN, we must address two challenges: 1) how to eliminate the installation of a user application, and 2) how to reduce network traffic. The first challenge follows the definition of the on-demand characteristic from the users' perspective. The second challenge is related to the nature of mesh networks. AWPN has limited communication bandwidth because of the significant volume of forwarding transmissions, which places a restriction on localization latency and the number of users.

Therefore, this paper introduces a distributed localization system that provides on-demand characteristics from both the service providers' and users' perspectives. The proposed localization system requires no specific user application; rather, it uses Web browsers. We install a Web server on each WiFi AP. Then, each AP measures the received signal strength indicator (RSSI) of the signal of a WiFi device and sends the RSSI-data to the Web server that the WiFi device accesses. The Web server calculates the location of the WiFi device and updates the Web contents. There is a W3C Geolocation API that provides a localization function on the Web browsers; the API depends on GPS or a site survey to build an AP fingerprint database.

By conducting experiments using actual WiFi APs, we demonstrate the feasibility of the proposed system and evaluate basic performances in a real environment. We also analyze the design and perform simulations to validate that the proposed distributed localization system generates less network traffic than a centralized system.

Specifically, our main contributions are threefold:

- We present the design of an on-demand location-based Web service that eliminates the installation of a user application. To the best of our knowledge, this is a first WiFi localization work addressing both the cost of

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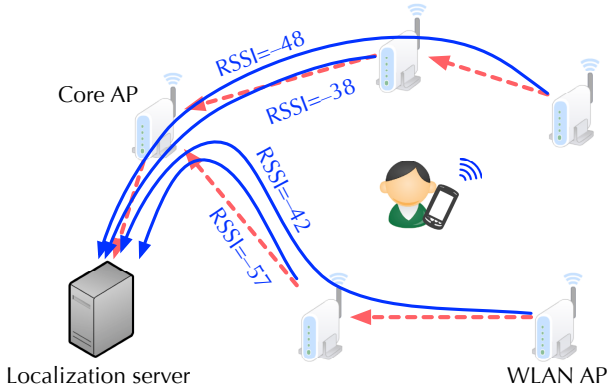


Fig. 1. Overview of ad-hoc wireless positioning network

installation of the user application and deployment in the field.

- We mathematically formulate the network traffic model of localization on the AWPN. Using this traffic model, we theoretically demonstrate that the proposed distributed localization system generates less traffic than a centralized localization system.
- We demonstrate the effectiveness of the proposed distributed localization system with experimental evaluations using actual WiFi APs and simulations.

The remainder of this paper is as follows. Section II describes the AWPN and the challenges to implement on-demand location-based services. We present a design of the proposed system in Section III and analyze the design in Section IV. Section V describes the implementation of the on-demand location-based service and presents the experimental evaluations. In Section VI, we conduct simulations and confirm the network traffic performance. Finally, Section VII concludes the paper.

II. ON-DEMAND LOCATION-BASED SERVICE

A. Ad-hoc Wireless Positioning Network

AWPN is a WiFi mesh network with the capability of localizing WiFi devices [25]. Figure 1 presents an overview of AWPN. To implement AWPN, we install multiple WiFi APs over the localization target area and connect a localization server to an AP called the core AP. The network is then automatically constructed using multi-hop communication between the APs. Registering the locations of the APs to the localization server, we complete the AWPN implementation.

When a WiFi device transmits a WiFi signal in the localization target area, the localization process is initiated. The WiFi APs that detect the signal retrieve the RSSI and send the RSSI-data to the localization server. The localization server calculates the location of the WiFi device using triangulation with the RSSI-data received from multiple APs.

B. Challenges

With AWPN, we can instantly build a localization infrastructure. To realize the on-demand characteristic from the users' perspective, there are two challenges.

- 1) *How to eliminate installation of user applications?:* Consider a navigation system at an exhibition venue. We

can assume that visitors will be one-time users who use the navigation system on that day only. Current indoor WiFi localization systems force users to install their own user application to use service-specific information and to provide location-based services. People tend to avoid installing such one-time applications creating a challenge to motivating people to use the service.

- 2) *How to reduce network traffic?:* Because the localization server collects all the RSSI-data via a multi-hop network, the communication bandwidth is limited by the core AP. The congestion at the core AP places a restriction on the number of users and results in considerable communication latency, which directly affects localization latency.

C. Related Works

To the best of our knowledge, a localization system addressing the installation cost of both the infrastructure and user side is novel in the field of WiFi localization. The consideration of network traffic for localization is also unique because the majority of the work on WiFi localization implicitly assumes that the network capacity is sufficiently large. Because there is an extensive amount literature discussing WiFi localization, in this subsection we limit our review of WiFi localization to research that does not requires special hardware.

Because of its high accuracy, a popular method in WiFi localization is fingerprinting [26]. Fingerprinting research focuses primarily on accuracy improvement [1–6] and a reduction in computational cost [10]. The high accuracy of fingerprinting is achieved using a site survey that collects enormous amounts of RSSI-data to construct a fingerprint database. Because our goal is implementing on-demand location-based services, it is often difficult to conduct a site survey prior to the use of the services.

Some works attempt to reduce the cost of a site survey by crowdsourcing [15–18]. These works continue to require user cooperation to collect considerable data before localization.

LiFS [19], Zee [20], UnLoc [21], and WILL [22] extend a crowdsourcing technique to eliminate explicit user cooperation. These works combine RSSI with users' locations derived from sensors such as accelerometers, compasses, and gyroscopes. EZ [23] is also categorized in this group. It constructs a radio propagation model rather than a fingerprint database. There are other works that use sensors such as acoustic sensors to improve accuracy [7–9]. These methods require the use of specific user applications to retrieve sensor data.

In contrast to the fingerprinting approach, model-based localization using RSSI requires no site survey. Model-based localization systems calculate the distance between a transmitter and a receiver using a radio propagation model and calculate the location using tools such as triangulation.

The primary advantage of model-based localization is ease of deployment. Studies on the model-based localization enhance this advantage. LEASE [24] proposes a nonparametric radio propagation model to reduce the number of required infrastructure devices such as WiFi APs. These types of techniques are also useful for the proposed distributed localization system to reduce the deployment cost.

In model-based localization, accuracy improvement is another research topic. Works such as Palantir [11] identify and address challenges to improve accuracy; however the accuracy is less than the fingerprinting scheme. Several studies using other radio systems such as RFID [12], UWB [13], and ZigBee [14] have also reported on accuracy improvement. Some of these are useful for the proposed on-demand location-based services to improve accuracy.

III. SYSTEM DESIGN

A. Primary Approach

Our primary approach to address the first challenge, i.e., elimination of a user-application installation process, is to implement the on-demand location-based service as a Web service. The Web server functions as a localization server. Users can instantly access the location-based service with Web browsers, which are usually pre-installed on WiFi devices.

For the second challenge, i.e., the reduction in network traffic, we employ two approaches:

- 1) We install Web servers on all WiFi APs and force users to access the Web server on the AP associated with the user device. In this manner, we can reduce the communication hop counts for the RSSI-data transfer because the device is usually associated with a neighboring AP. Consequently, we can reduce the total network traffic by decreasing the forwarding traffic. We note that it is easy to redirect user access to the Web server in the associated AP using a RADIUS server.
- 2) We design the proposed localization system as an autonomous distributed system on the WiFi APs; each AP operates autonomously to localize the user devices. The autonomous operation requires no control packets for tasks such as collecting RSSI-data and synchronization.

B. System Overview

The proposed distributed localization system consists of three servers on each AP: a Web server, an RSSI reception server, and an RSSI detection server. Localization is performed by the autonomous operation of the three servers on multiple APs: the Web server and the RSSI reception server on the AP associated with a user device, and the RSSI detection server in the APs close to the device.

Figure 2 illustrates the sequence of localization in the proposed distributed localization system. Users first turn on a WiFi module on their WiFi device and associate the device with one of the WiFi APs. 1) Users then access the Web server in the associated AP using a Web browser. 2) The Web server returns a location-based service Web page. 3) The Web browser periodically sends a localization request to the Web server. 4) The Web server waits for a fixed duration while the RSSI reception server collects RSSI-data from other APs. 5) The RSSI detection servers in all the APs sniff the localization requests. 6) In the APs that detect a localization request signal, the RSSI detection server measures the RSSI of the signal. 7) The RSSI detection server combines the RSSI with other information such as the IP address of the user device and generates the RSSI-data. The RSSI-data is then sent to the RSSI reception server in the AP associated with the WiFi device. Note that the RSSI detection server in the associated

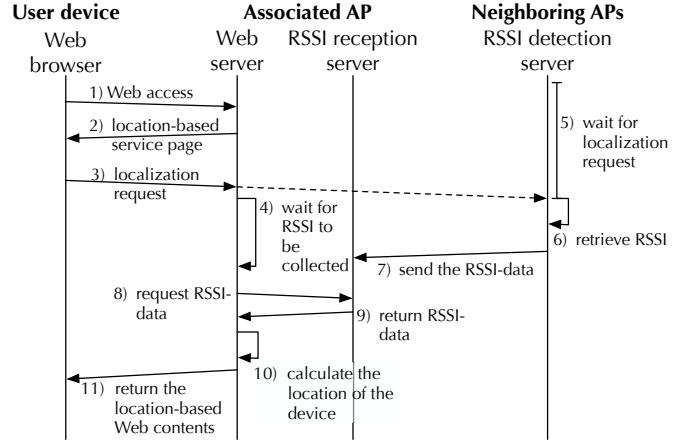


Fig. 2. Sequence diagram of the proposed distributed localization system

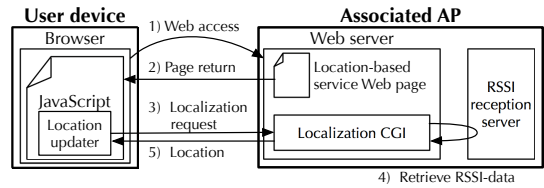


Fig. 3. Operation of the Web server

AP also retrieves the RSSI and sends the RSSI-data. 8) The Web server requests the RSSI-data of the user device from the RSSI reception server. 9) The RSSI reception server returns a set of RSSI-data. 10) The Web server calculates the location of the user device. 11) The Web server finally returns the Web content that is dependent on the calculated location.

The following subsections describe the autonomous operation of the three servers in detail.

C. Web Server

The Web servers provide a location-based Web page and a localization common gateway interface (CGI) program. Using an Ajax (Asynchronous JavaScript and XML) scheme, we periodically update the Web contents based on the user location.

Figure 3 depicts the operation of the Web server. 1) When a user accesses the Web server, the Web server redirects to the location-based Web service page and 2) returns the page. 3) A JavaScript program called location updater on the location-based service page periodically accesses a localization CGI on the Web server. The CGI program retrieves the IP address of the remote host making the request, i.e., the user device. After a certain duration, 4) the CGI program retrieves a set of RSSI-data from the RSSI reception server using the retrieved IP address as a search key. 5) The CGI program calculates the location of the user device and returns the location. The JavaScript program finally updates the Web contents based on the calculated location.

For autonomous operation, we must determine the wait duration in the CGI program. The wait duration, which this is the period the CGI program should wait for the RSSI-data to be collected, should be minimized for real-time operation. We

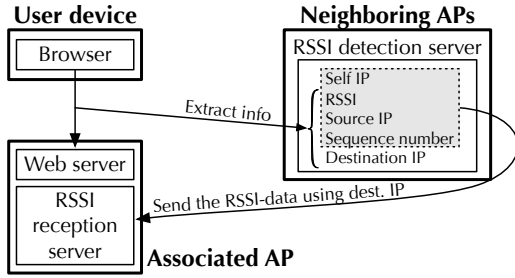


Fig. 4. Operation of the RSSI detection server and the RSSI reception server

determine the wait duration experimentally in Section V-D.

D. RSSI Detection Server & RSSI Reception Server

Figure 4 presents the operation of the RSSI detection and RSSI reception servers. The RSSI detection server in all WiFi APs continuously attempts to sniff the localization requests sent from the user devices. When the RSSI detection server sniffs at a localization request, the server collects the following four values:

- 1) RSSI, which is mandatory for the calculation of the location. We can retrieve the RSSI from the WiFi module.
- 2) Source IP address, i.e., the IP address of the remote host, which is used as a search index when a localization CGI program requests a set of RSSI-data. We can retrieve the source IP address from the IP header because the localization request is an IP packet.
- 3) Sequence number, which is used in the localization CGI program to acquire the latest RSSI-data. We use the Sequence Control value of the Frame Control field in the IEEE 802.11 MAC header for TCP/IP re-transmissions.
- 4) Destination IP address, i.e., an IP address of the AP associated with the user device. We can retrieve the destination IP address from the IP header.

The RSSI detection server assembles the RSSI, the source IP address, the sequence number, and destination IP address to generate the RSSI-data. The RSSI-data is then sent to the RSSI reception server at the destination IP. In this manner, the RSSI-data generated by one localization request is collected on the RSSI reception server in the AP associated with the user device.

The RSSI reception server functions as a simple database of RSSI-data. The RSSI reception server receives RSSI-data from the RSSI detection servers and stores the RSSI-data. When a localization CGI requests a set of RSSI-data with an IP address as a search key, the RSSI reception server selects and returns a set of the latest RSSI-data whose source IP address is equal to the key IP address.

E. Design Limitations

Although our design addresses the two challenges described in Section II-B, there are three significant limitations:

- 1) *No encryption on WiFi communication*: For autonomous operation, WiFi APs sniff localization request signals from WiFi devices and extract information such as the

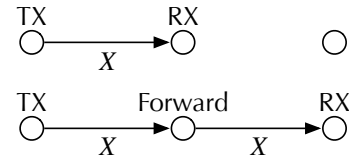


Fig. 5. Network traffic in line-topology networks. An increase in hop count results in an increase in network traffic because of forwarding transmissions.

IP address. To extract this information, we cannot use encryption such as WEP or WPA-PSK on the WiFi communication. Encryption could be implemented if the CGI program acquire a MAC address rather than an IP address.

- 2) *Single channel network*: WiFi APs sniff localization request signals; this restricts the WiFi APs to one specific channel. If each AP used a separate channel, the APs would be required to switch their sniffing channels to not miss the localization request signals.
- 3) *Limited resources for localization calculation*: The localization CGI program calculates the device location on the WiFi AP. Because WiFi APs have limited computational resources, it is not practical to use a complex calculation algorithm. We could offload some of the calculation to a JavaScript program executing on the user devices.

Despite these limitations, we believe the proposed distributed localization system is valuable for simple location-based services.

IV. DESIGN ANALYSIS

A. Definition of Network Traffic

We define network traffic T as the data transmitted by all WiFi APs per unit time:

$$T = \sum_i T_{i(tx)}, \quad (1)$$

where $T_{i(tx)}$ is the traffic of AP i , i.e., the data transmitted by AP i per unit time including forwarding transmissions.

Consider the RSSI-data transfer in line-topology networks indicated in Fig. 5 as a simple example. Let X be the size of the RSSI-data generated on one WiFi AP per unit time. In the upper case of Fig. 5, one WiFi AP transmits the RSSI-data X ; we can instantly calculate the network traffic to be $T = X$. In a similar manner, the network traffic in the lower case of the figure is calculated to be $T = 2X$. In general, network traffic of an h -hop network that transfers single RSSI-data traffic is calculated to be $T = hX$.

B. Assumptions

In the proposed system, one or more WiFi APs detect signal from one WiFi device, which results in multiple RSSI-data traffic. To simplify the traffic analysis, we apply specific assumptions:

- All APs construct a mesh network.
- Each AP has the same constant number N_d of associated WiFi devices.
- For one WiFi device, the RSSI-data is generated by APs within one hop of the AP associated with the device.

- One WiFi AP generates RSSI-data X per unit time.

In the following subsection, we prove that the network traffic in the proposed distributed localization system is less than or equal to that in a centralized system under the same assumptions. These assumptions are, of course, not always true. The number of associated devices varies. Further, WiFi devices are not necessarily detected by all the APs neighboring the associated AP; they could be detected by APs distant from the associated AP. We perform network simulations to evaluate network traffic in a more realistic scenario in Section VI.

C. Traffic Modeling

We use a graph $G = (V, E)$ to describe the AP mesh network: a vertex set V describes the APs and an edge set E describes the links between the APs. Under our assumptions, G is a simple connected graph.

We first calculate the network traffic in the proposed distributed localization system.

Lemma 1. *Network traffic T_d in a distributed localization system is equal to $2N_d X |E|$.*

Proof: Consider the case where one WiFi device is associated with AP $v \in V$. RSSI-data is generated by v and the APs neighboring v . Let $N(v)$ be the neighboring APs. T_d is calculated by summing the N_d devices and for all the APs:

$$T_d = N_d X \sum_{v \in V} \left\{ d(v, v) + \sum_{n \in N(v)} d(n, v) \right\}, \quad (2)$$

where $d(x, y)$ is the distance between the vertices x and y . Clearly, $d(v, v) = 0$ and $d(n, v) = 1$ because n is a neighbor of v . We therefore derive:

$$T_d = N_d X \sum_{v \in V} |N(v)| = N_d X \sum_{v \in V} d(v) = 2N_d X |E|, \quad (3)$$

where $d(v)$ is a degree of v , i.e., the number of edges at v . ■

We next calculate the network traffic in a centralized localization system. In a centralized system, all RSSI-data is transferred to a specific AP called a core AP.

Lemma 2. *Let $z \in V$ be a core AP in a centralized localization system. Network traffic T_c in the centralized system is more than or equal to $N_d X \{|V| - 1 + 2|E| - d(z)\}$.*

Proof: Consider the case where one WiFi device is associated with AP $v \in V$. RSSI-data is generated by neighboring APs $N(v)$ and v . All RSSI-data is transferred to the core AP z . Network traffic is therefore calculated to be:

$$T_c = N_d X \sum_{v \in V} \left\{ d(v, z) + \sum_{n \in N(v)} d(n, z) \right\}. \quad (4)$$

When $v = z$, $d(v, z) = 0$ and $d(n, z) = 1$. We separately calculate the first sum in Eq. (4) for $v = z$ and derive¹

$$T_c = N_d X d(z) + N_d X \sum_{v \in V - z} \left\{ d(v, z) + \sum_{n \in N(v)} d(n, z) \right\}. \quad (5)$$

¹Instead of $V \setminus \{z\}$, we simply write $V - z$.

TABLE I
MAIN SPECIFICATIONS OF PCWL-0100 [27]

Range in line-of-sight	Approximately 150 m (varies with propagation environment)
TX power of mesh wireless	16 dBm
TX power of access wireless	16 dBm
Number of mesh wireless IFs	2 (except an access wireless IF)
	5.15 ~ 5.35 GHz
Access wireless standard	IEEE 802.11b/g
Physical dimensions	W 142 mm × H 118 mm × D 39 mm
Weight	450 g

To calculate the lower bound of Eq. (5), consider the distance in Eq. (5) for the two cases below:

- 1) $n = z$
 $d(v, z) = 1$ and $d(n, z) = 0$;
- 2) $n \neq z$
 $d(v, z) \geq 1$ and $d(n, z) \geq 1$.

There is an $n \in N(v)$ such that $n = z$ if and only if $v \in N(z)$. The number of times that Case 1 occurs is therefore $|N(z)| = d(z)$. Substituting $d(v, z) = 1$, $d(n, z) = 1$ for Eq. (5) and subtracting the traffic for Case 1, we finally derive the lower bound:

$$T_c \geq N_d X \left\{ d(z) + |V| - 1 + \sum_{v \in V - z} d(v) - d(z) \right\} \\ \geq N_d X \{|V| - 1 + 2|E| - d(z)\}. \quad (6)$$

Finally, we compare the network traffic.

Theorem 1. *The network traffic T_d in the distributed localization system is less than or equal to the network traffic T_c in the centralized localization system.*

Proof: From Lemmas 1 and 2, we can compare T_d with the lower bound of T_c . Subtracting Eq. (3) from Eq. (6), we derive

$$T_c - T_d \geq N_d X \{|V| - 1 - d(z)\}. \quad (7)$$

Because G is not a multigraph, vertex z has at most $|V| - 1$ edges:

$$|V| - 1 - d(z) \geq 0. \quad (8)$$

Clearly, $N_d \geq 0$, $X \geq 0$, and the theorem follows. ■

V. EXPERIMENTAL EVALUATION

A. Implementation

To demonstrate the feasibility and to evaluate the basic performances, we implemented the proposed distributed localization system and a sample location-based Web service on actual WiFi APs. We used PCWL-0100 (PCWL) WiFi APs from PicoCELA Inc [27]. Table I presents the main specifications of the PCWL. The PCWL is a WiFi AP having a relay function and can automatically construct a mesh network using multi-hop communication.

We implemented the Web server, the RSSI detection server, and the RSSI reception server on the embedded Linux running on the PCWL.

We installed a lightweight open source Web server *thttpd* on all the WiFi APs. The localization CGI program was implemented as a C program. To calculate the location of



Fig. 6. PCWLs installed on the ceiling and wall



Fig. 7. Example location-based service. Google Chrome on an iPad displaying an indoor map and the user location

the user devices, we used a simple triangulation algorithm with the propagation model suggested by ITU-R [28] because high accuracy was not an object. We used shared memory for simplicity of the communication between the CGI program and the RSSI reception server.

The RSSI detection server and the RSSI reception server were also implemented as C programs. The RSSI detection server captured all the WiFi frames on a monitor mode interface using a MadWifi driver. The RSSI detection server then analyzed the WiFi frames with a Radiotap header and extracted the RSSI, source IP address, sequence number, and destination IP address to generate the RSSI-data. The RSSI-data was transmitted to the RSSI reception server using TCP/IP communication.

B. Experiment Environment

We conducted experiments in our university building. We installed 30 PCWLs, i.e., WiFi APs, on the ceilings and walls as indicated in Fig. 6 and implemented an indoor map Web service to indicate a user location. Figure 7 is an example of the proposed location-based service. In Fig. 7, the blue circle depicts the location of a user device and the red circles depict the WiFi APs.

We installed a laptop with a WiFi module and accessed the proposed location-based service Web page using Google Chrome web browser. We collected the logs from the three servers in terms of the communication and localization calculation for approximately 20 minutes. The location updater JavaScript was configured to send localization requests every 10 seconds. We observed the localization calculation for 125 instances.

C. Number of RSSI-Data Transmissions

To confirm that the APs near to the user device detect the location request signal, we evaluated the number of RSSI-data transmissions. The number of RSSI-data transmissions equals the number of location requests detected on the WiFi APs.

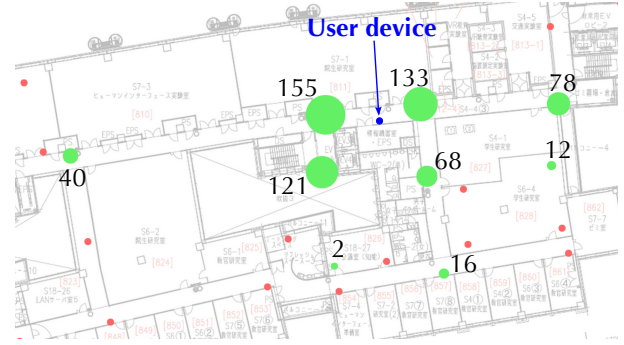


Fig. 8. Number of RSSI-data transmissions on each WiFi AP. Diameter of green circles indicates the number of transmissions; red circles imply no transmission. The number beside the green circles is the actual number of transmissions.

Figure 8 presents the number of RSSI-data transmissions on each WiFi AP. Each circle describes the location of a WiFi AP. The green circles indicate that there was at least one RSSI-data transmission; the red circles indicate no transmission. The number beside the green circles is the number of transmissions and the diameter of the green circles visually indicates the number of transmissions. We note that the user device was associated with the AP that transmitted RSSI-data 133 times. Figure 8 illustrates the following:

- 1) The WiFi APs close to the user device detected a greater number of signals. Neighboring APs have a higher probability of signal detection than the APs distant from the user device because the neighboring APs receive a greater power signal.
- 2) On some APs, the number of transmissions was greater than the number of localization calculations of 125. This is because there were some retransmissions in the TCP and the IEEE 802.11 MAC layers.
- 3) There was a case where a WiFi AP distant from the user device detected the location request signal. In our experiment, the distance between the user device and the farthest AP that transmitted RSSI-data was approximately 30 meters. Because the farthest AP and the device were in line-of-sight distance, the farthest AP sometimes detected the WiFi signal from the user device.

The above results reveal that the majority of the RSSI-data was collected from the APs close to the user device.

D. Communication Latency for RSSI-Data Collection

To determine the wait duration in the localization CGI program described in Section III-C, we evaluated the communication latency for the RSSI-data collection. Communication latency is defined as the time length from the first reception of the RSSI-data to the last reception in the RSSI reception server. In this definition, we ignore the time from a localization request to the first reception of the RSSI-data. This definition is valuable because the RSSI reception server immediately receives the RSSI-data from the RSSI detection server in the same AP.

Figure 9 presents a histogram of the communication latency for the RSSI-data collection. The mean communication latency was 88.8 milliseconds and the maximum communication latency was 2,999.7 milliseconds. The minimum communication

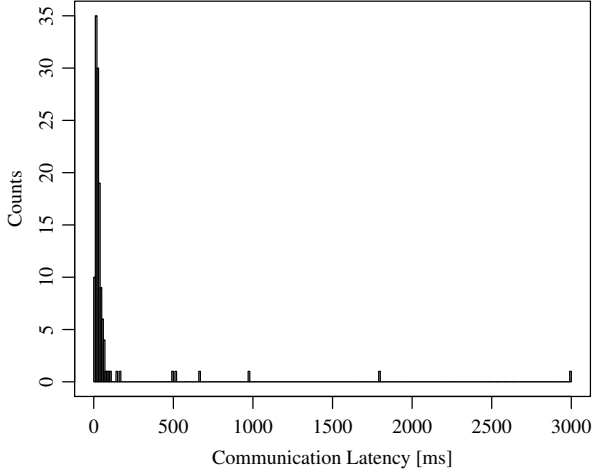


Fig. 9. Histogram of communication latency for RSSI-data collection

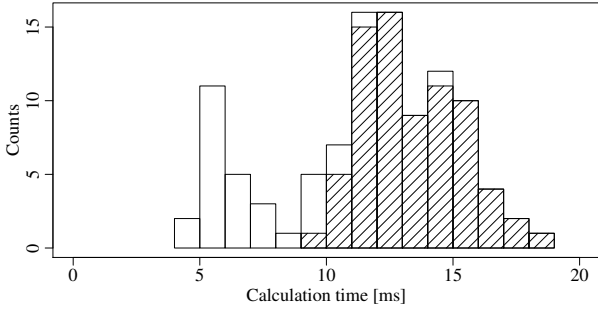


Fig. 10. Histogram of the calculation of latency for localization. Shadow bar describes calculation latency for successful localizations.

latency was zero, which was the case when only one RSSI-data was received. Figure 9 indicates the following:

- 1) More than 95 % of the RSSI-data collections were completed within 200 milliseconds. Small communication latency was achieved because majority of the RSSI-data was generated on APs near to the AP associated with the user device.
- 2) Communication latency sometimes required more than 500 milliseconds because the PCWLs construct a network path on the first data transfer, which sometimes required several seconds.

Considering the characteristics of a location-based service, we can determine the wait duration in the localization CGI program. In our case of a map application, for example, the location of the user should appear as early as possible and a localization failure is allowed. We therefore used 200 milliseconds as the wait duration.

E. Calculation Latency for Localization

Localization latency is defined as the sum of the wait duration in the localization CGI program and calculation latency for localization. In the previous section, we determined the wait duration in the localization CGI program. To estimate the localization latency, we evaluated the calculation latency.

Figure 10 presents the histogram of the calculation latency for localization. The shadow bar describes the calculation

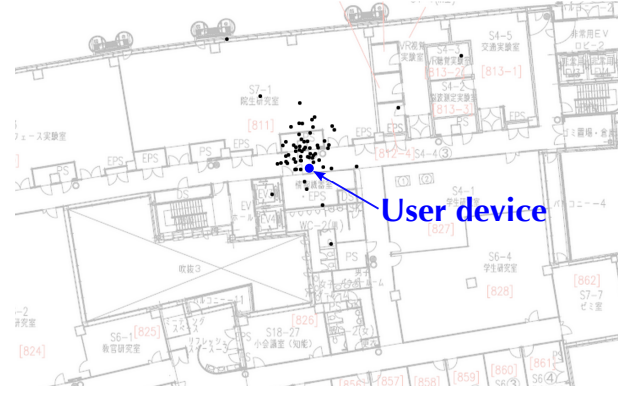


Fig. 11. Localization results

latency for successful localizations. Calculations sometimes fail because the number of RSSI-data is not sufficient for triangulation. Figure 10 indicates the following:

- 1) Unsuccessful localizations completed in less time than successful localizations. This is because it was impossible for the localization CGI program to calculate the location in the early stage of the calculation. The calculation failed with an insufficient number of RSSI-data.
- 2) There were some cases where the unsuccessful localization required more than 14 milliseconds. The calculation sometimes diverged because of the variations of RSSI caused by multi-paths and measurement errors.

The above results reveal that all the calculations completed within 20 milliseconds. The maximum localization latency was therefore 220 milliseconds.

F. Localization Error

Although we did not aim for high accuracy, we evaluated the localization error to demonstrate that the proposed system could provide location-based services. Figure 11 presents the localization results and indicates the following:

- 1) Our system can identify the approximate location of a user device. The mean localization error was 4.8 meters.
- 2) There was occasionally considerable localization error. This was primarily because we employed simple triangulation. As described in Section II-C, there are numerous works on accuracy improvement. Some of these works would be helpful to improve accuracy.

VI. SIMULATION

In our experiment, we were unable to monitor forwarding traffic owing to a limitation of the PCWLs. To demonstrate the effectiveness of the proposed distributed localization system in terms of network traffic, we performed a network simulation using ns-3. We assumed that WiFi devices were uniformly distributed and moved in a localization area. Each WiFi device connected to an AP near the device, which removed some of the impractical assumptions presented in Section IV-B.

A. Simulation Environment

Our distributed localization system uses two kinds of network: a mesh network for communication between the WiFi

TABLE II
SIMULATION ENVIRONMENT

Mesh wireless standard		IEEE 802.11s (5-GHz band)
Access wireless standard		IEEE 802.11b (2.4-GHz band)
WiFi devices	Number of devices	20 ~ 140
	Initial position	Uniform random
	Mobility model	Random waypoint
Localization interval		1 s
RSSI-data size		11 bytes
Simulation time-length		30 s
Number of trials		1000

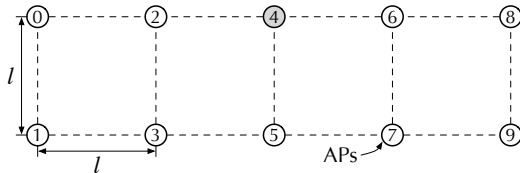


Fig. 12. Arrangement of WiFi APs. Dotted lines indicate network paths. $l = 50$ [m]. In a centralized system, the core AP is 4.

APs and an access network for communication between the WiFi APs and WiFi devices. We used IEEE 802.11s with a single channel in a 5-GHz band to build the mesh network. For the access networks, we built an IEEE 802.11b network. All access networks used the same channel in a 2.4-GHz band because the APs must detect the signals from all the WiFi devices in the system.

We arranged ten WiFi APs as a 2×5 grid with 50-meter spacing as illustrated in Fig. 12. The WiFi devices were uniformly distributed and moved around this grid area. We used the “random waypoint” model for device mobility.

We changed the number of WiFi devices from 20 to 140 and performed 1,000 simulation trials for each number of WiFi devices. Each device transmitted a localization request signal via an access network every second to the AP associated with the device. The WiFi APs that detected the localization request signal generated RSSI-data and transferred the RSSI-data to the associated AP. The RSSI-data was transferred using UDP/IP communication instead of TCP/IP to exclude the influence of ACKs and retransmissions. We used RSSI-data of 11 bytes, the same data size as our experiment. Each trial simulated a 30-second communication. For other configurations, we used the default values defined in ns-3.

Table II summarizes our simulation environment. Under this environment, we simulated communication and collected transferred data sizes on all the APs. We compared the performance of two systems:

1) Distributed system (proposed)

The distributed system is the proposed system presented in Section III. In the distributed system, a location-based service is implemented on the distributed Web servers in all the APs. Each WiFi device accessed a Web server in the AP associated with the device. Each AP measured the RSSI of the signal from the device and sent the RSSI-data to the associated AP.

2) Centralized system

The centralized system is a localization system using a normal AWPN as described in Section II-A. In the centralized system, a location-based service was imple-

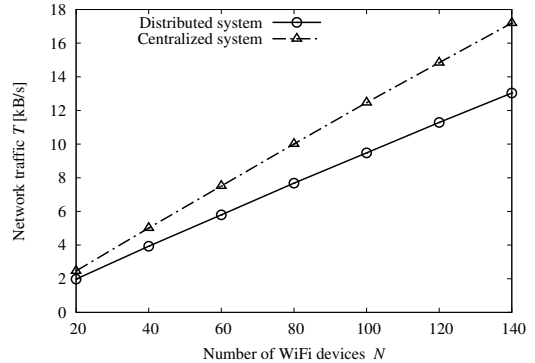


Fig. 13. Network traffic T as a function of the number of WiFi devices N

mented on a single Web server connected to a core AP. Each AP measured the RSSI of the WiFi device and sent the RSSI-data to the Web server. The core AP was AP “4” in Fig. 12.

B. Network Traffic

Network traffic was calculated by summing the transmission data size and forwarding the data size over all the APs. Because we defined the network traffic as the total transferred data size per unit time in Section IV, we divided this total data size by the simulation time-length. We calculated the network traffic for every trial and averaged the network traffic.

Figure 13 presents the network traffic as a function of the number of WiFi devices. Figure 13 indicates the following:

- 1) Network traffic was approximately proportional to the number of devices in both the distributed and centralized system.
- 2) Network traffic in the distributed system was less than that in the centralized system. The network traffic was reduced by approximately 20.0 % at $N = 20$ and 24.1 % at $N = 140$. Forwarding traffic in the distributed system was less than that in the centralized system, which resulted in a significant decrease in network traffic.

The above simulation results confirm that the proposed distributed system generates less network traffic than the centralized system.

C. AP traffic

As described in Section II-B, congestion in the network results in localization latency. To demonstrate that the proposed localization system can avoid a concentration of traffic on specific APs, we evaluated the maximum AP traffic and standard deviation. The AP traffic is data transmitted by one AP per unit time.

Figure 14 presents the maximum AP traffic and the standard deviation as a function of the number of WiFi devices. Figure 14 indicates the following:

- 1) The maximum AP traffic in the proposed distributed system was approximately 60 % of that in the centralized system. This is because traffic does not concentrate on one AP in the proposed distributed localization system, whereas traffic on the core AP is significant in a centralized system.

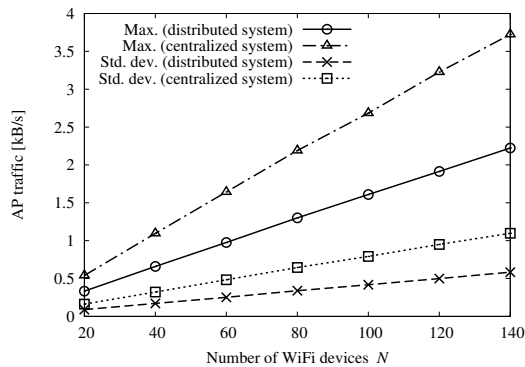


Fig. 14. Maximum and standard deviation of AP traffic as a function of the number of WiFi devices N

- 2) The standard deviation of the AP traffic in the proposed distributed system was less than half of that in the centralized system. This is because the physical distribution of the WiFi devices distributes the network traffic over a mesh network in the distributed system.

The above simulation results confirm that the proposed system distributes traffic over the network.

VII. CONCLUSION

In this paper, we presented a distributed localization system to implement on-demand location-based services. We realized on-demand characteristics from both the service providers' and users' perspectives. From the service providers' view, we utilized our previous work, AWPn. From the users' perspective, we addressed two challenges: elimination of a user-application installation process and reduction in network traffic. We provided a location-based service as a Web service that could be utilized via Web browsers. With Web servers installed on all the WiFi APs, the proposed localization system reduced network traffic by reducing forwarding traffic. Design analysis confirmed that network traffic in the proposed distributed localization system was less than or equal to that in a centralized system. We implemented the proposed localization system on actual WiFi APs and conducted experimental evaluations. The evaluation results demonstrated that the proposed system could localize a user device within 220 milliseconds. By performing simulations, we also confirmed that the proposed system could reduce network traffic by approximately 24 % compared to that in a centralized system.

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