

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

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Abstract—WiFi-based localization is a promising candidate of indoor localization. In this paper, we present a distributed localization system using a WiFi ad-hoc wireless positioning network (AWPN) to realize *on-demand* location-based services. The AWPN is a WiFi mesh network with the capability of localizing WiFi devices. Using the AWPN, we can easily build a localization infrastructure by putting WiFi APs. To realize *on-demand* location-based services, we tackle two challenges: reduction in the installation cost of the user application and reduction in network traffic. We design a localization system using the AWPN and realize an on-demand location-based service as a Web service, which enables us to use via Web browsers. Our localization system is built on WiFi APs and distributes network traffic over the network. The experimental evaluations show that our localization system can localize a user device within 220 milliseconds. We also performed simulations and reveal that our localization system reduces network traffic by up to 24 % than that in the 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 more required to extend location-based services to indoor environment. Many localization technology using such as ultrasound, infrared light, and WiFi signal have been developed. Especially, WiFi localization technology is gaining its importance in terms of deployment cost. The WiFi localization system can be built on existing WiFi devices, which results in low deployment cost.

Our goal is to realize *on-demand* indoor location-based services using WiFi localization technology. In an exhibition event, for example, there is a demand of a navigation system since exhibitions are usually held in a large site. The exhibitions take place for only few days, it is important to reduce deployment cost.

To reduce deployment cost, we have developed a WiFi ad-hoc wireless positioning network (AWPN) that can temporarily and easily provide a localization system in both indoor and outdoor environment [1]. The AWPN is a localization system using WiFi mesh network technology [2]. In the AWPN, multiple WiFi access points (APs) are distributed over the localization target area. Each AP captures WiFi signal from WiFi devices and measures the signal strength, i.e. received signal strength indicator (RSSI). The RSSI-data is then sent to

a localization server. The localization server finally calculates the location of the WiFi devices. Using the AWPN, we can easily build a localization infrastructure by only putting WiFi APs and a localization server.

Toward the goal of realizing *on-demand* indoor location-based services using the AWPN, there are two more challenges. The first challenge is reduction in the installation cost of user application. Consider a navigation system in the exhibition scenario. Since visitors will use the navigation system for only few days, reducing obstacles to using the system is important. The second challenge is reduction in network traffic. The AWPN has limited communication resources due to the nature of multi-hop network. The limited resources place a restriction on the number of users and on localization latency.

Previous works on WiFi localization have primarily studied on improvement in accuracy [3–16] or reduction in deployment cost [17–27]. There has been tiny interest in user applications and network traffic for localization.

In view of this, this paper introduces a distributed localization system that realizes an on-demand location-based service as a Web service on the AWPN. Our localization system requires no specific user application but uses Web browsers. We install a Web server on each WiFi AP. The each AP measures RSSI of the signal from a WiFi device and sends the RSSI-data to the Web server which the WiFi device accesses. The Web server calculates location of the WiFi device and updates the Web contents.

By conducting experiments using real WiFi APs, we show the feasibility of our system and evaluate basic performances in real environment. We also perform simulations to show that our distributed localization system can reduce network traffic compared to the centralized system.

Specifically, our main contributions are twofold:

- We present the design of an on-demand location-based Web service which eliminates installation of user applications. To the best of our knowledge, this is a first work tackling the cost of both installation of user applications and deployment in the field of WiFi localization.
- We show the effectiveness of our distributed localization system by experimental evaluations using real WiFi APs as well as simulations.

The remainder of this paper is as follows. Section II de-

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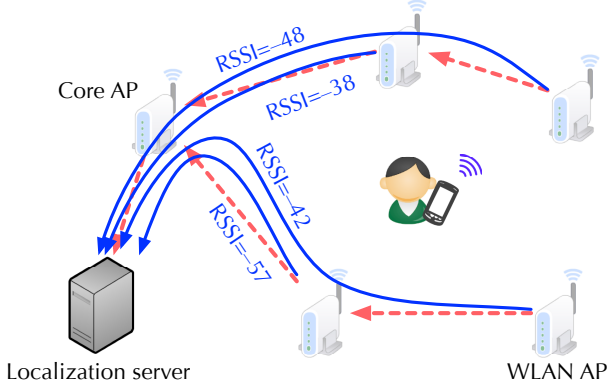


Fig. 1. Overview of ad-hoc wireless positioning network.

scribes the AWPN as well as challenges to realize on-demand location-based services. We present a design of our system in Section III. Section IV describes implementation of the on-demand location-based service and conducts experimental evaluations. In Section V, we perform simulations and show the network traffic performance. Finally, Section VI concludes the paper.

II. ON-DEMAND LOCATION-BASED SERVICE

A. Ad-hoc Wireless Positioning Network

The ad-hoc wireless positioning network (AWPN) is a WiFi mesh network with the capability of localizing WiFi devices [1]. Figure 1 shows the overview of the AWPN. To set up the AWPN, we put multiple WiFi APs over the localization target area and connect a localization server to the AP called a core AP. Network is then automatically constructed by multi-hop communication between APs. Registering the locations of the APs to the localization server, we finish setting up the AWPN.

When a WiFi device transmits a WiFi signal in the localization target area, the localization process is initiated. The WiFi APs retrieve the received signal strength indicator (RSSI) and send the RSSI-data to the localization server. The localization server calculates the location of the WiFi device by such as triangulation using RSSI-data received from multiple APs.

B. Challenges

With the AWPN, we can instantly build a localization infrastructure. To provide location-based services instantly, there are two challenges in the present AWPN.

- 1) Reduction in the installation cost of user applications: Consider a navigation system at an exhibition venue. We can guess that visitors will be one-time users who use the navigation system only on that day. Current indoor WiFi localization systems force users to install their own user applications to use service-specific information and to provide location-based services. As a result, users need to install and manage many applications for each event, which bothers the one-time users.
- 2) Reduction in network traffic: Since the localization server collects all the RSSI-data via multi-hop network,

the communication bandwidth is limited by a core AP. The congestion at the core AP places a restriction on the number of users and results in big communication latency, which directly affects localization latency.

C. Related Works

To the best of our knowledge, a localization system tackling the installation cost of both infrastructure side and user side has novelty in the field of WiFi localization. The view of network traffic for localization is also novel because most of the works on WiFi localization implicitly assume that the network capacity is sufficiently big. There is so much literature studying on WiFi localization, we briefly look into WiFi localization that requires no special hardware in this subsection.

One of the popular methods in WiFi localization is fingerprinting [28] due to its high accuracy. Fingerprinting researches mainly study on improvement in accuracy [3–8] as well as reduction in computational cost [12]. The high accuracy of fingerprinting is achieved by site survey which collects huge amount of RSSI-data to construct a fingerprint database. Since our goal is realizing *on-demand* location-based services, it is often hard to conduct the site survey prior to the use of the services.

Some works try to reduce the cost of site survey by crowdsourcing [17–20]. These works still require users' cooperation to collect much data before localization.

LiFS [21], Zee [22], UnLoc [23], and WILL [24] extend a crowdsourcing technique to eliminate explicit user cooperation. These works combine RSSI with users' location derived from sensors such as accelerometers, compasses, and gyroscopes. EZ [25] is also categorized in this group, which constructs a radio propagation model instead of the fingerprint database. There are some works that also use sensors such as acoustic sensors to improve accuracy [9–11]. These methods require the use of a specific user application to retrieve sensor data.

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

The main advantage of the model-based localization is easy deployment. Studies on the model-based localization enhance this main advantage. LEASE [26] proposes a non-parametric radio propagation model to reduce the number of required infrastructure devices such as WiFi APs. Zero-configuration localization [27] proposes an automatic configuration of the propagation model as well as WiFi AP locations. These techniques are also useful for our distributed localization system to reduce the deployment cost.

In the model-based localization, accuracy improvement is another research topic. Some works such as Plantir [13] show and tackle challenges to improve accuracy, yet the accuracy is lower than fingerprinting scheme. Several studies using other radio systems such as RFID [14], UWB [15], and

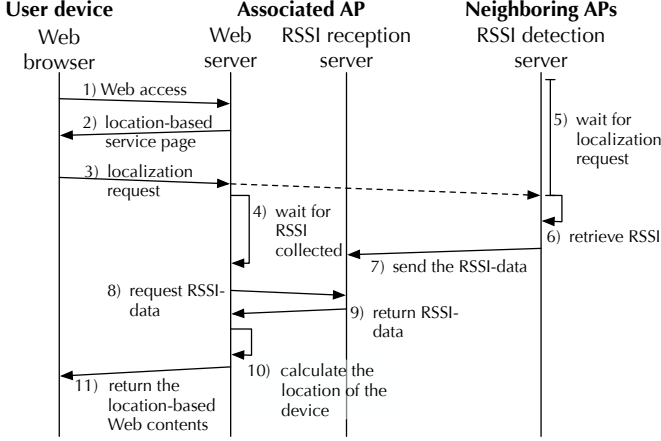


Fig. 2. Sequence diagram of our distributed localization system.

ZigBee [16] have also reported on accuracy improvement. Some of these works are also useful for our on-demand location-based services to improve accuracy.

III. SYSTEM DESIGN

A. Main Idea

Our main idea is quite simple for the first challenge. We realize an on-demand location-based service as a Web service. The Web server works as a localization server. Users can instantly access the location-based service with Web browsers installed on WiFi devices.

For the second challenge, i.e. 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 way, we can reduce communication hop counts for RSSI-data transfer since the device is usually associated with a neighboring AP. As a result, we can reduce total network traffic due to the decrease in forwarding traffic. We note that it is easy to redirect user access to the Web server in the associated AP using a RADIUS server, which is also useful for device handover.
- 2) We design our localization system as an autonomous distributed system on WiFi APs. Each AP operates autonomously to localize user devices. The autonomous operation requires no control packet for such as collecting RSSI-data and synchronization.

B. System Overview

Our 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 autonomous operation of three servers on multiple APs: the Web server and the RSSI reception server in the AP associated with a user device, and the RSSI detection server in the APs close to the device.

Figure 2 shows the sequence of localization in our distributed localization system. Users first turn on a WiFi module

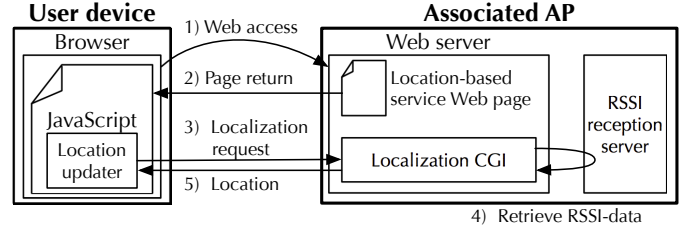


Fig. 3. Operation of the Web server.

on their WiFi device and associate the device with one of 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 so that the RSSI reception server collects RSSI-data from other APs. 5) The RSSI detection server in all APs try to detect the radio signal of localization requests. 6) In the APs which detect a localization request signal, the RSSI detection server retrieves RSSI of the signal. 7) The RSSI detection server combines the RSSI with other information such as an IP address of the user device and generates 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 AP also retrieves RSSI and sends the RSSI-data. 8) The Web server calls for RSSI-data of the user device to the RSSI reception server and 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 contents that depend 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 CGI program. Using the Ajax (Asynchronous JavaScript and XML) scheme, we periodically update Web contents based on 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 named 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 calculate the location of the user device and returns the location. The JavaScript program finally updates Web contents based on the calculated location.

For the autonomous operation, we need to determine the wait duration in the CGI program. The wait duration should be minimized for real-time operation, while the CGI program

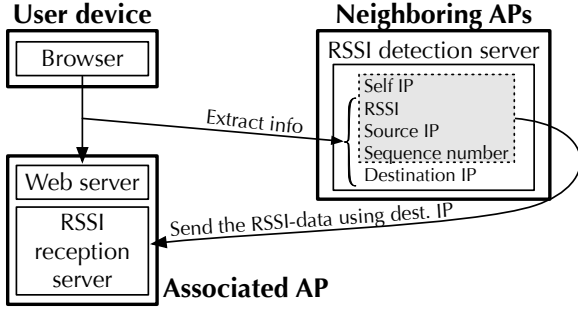


Fig. 4. Operation of the RSSI detection server and the RSSI reception server.

needs to wait for RSSI-data to be collected. We determine the wait duration experimentally in Section IV-D.

D. RSSI Detection Server & RSSI Reception Server

Figure 4 shows the operation of the RSSI detection server and the RSSI reception server. The RSSI detection server in all WiFi APs keep trying to sniff the localization requests sent from user devices. When the RSSI detection server sniffs the localization request, the server collects four values below:

- 1) RSSI, which is mandatory for the calculation of the location. We can retrieve the RSSI from a WiFi module.
- 2) Source IP address, i.e. an IP address of the remote host, which is used as a search index when a localization CGI program looks up a set of RSSI-data. We can retrieve the source IP address from an IP header since the localization request is an IP packet.
- 3) Sequence number, which is used in a localization CGI program to pick up the latest RSSI-data. We use Sequence Control value of a Frame Control field in an IEEE 802.11 MAC header to deal with TCP/IP retransmissions.
- 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 an IP header.

The RSSI detection server assembles the RSSI, the source IP address, the sequence number, and self IP address to generate RSSI-data. The RSSI-data is then sent to the RSSI reception server at the destination IP. In this way, 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 works 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 calls for a set of RSSI-data with an IP address as a search key, the RSSI reception server picks up and returns a set of latest RSSI-data whose source IP address equals to the key IP address.

E. Design Limitations

Although our design tackles two challenges described in Section II-B, there are two big limitations:

- 1) No encryption on WiFi communication: For the autonomous operation, the WiFi APs sniff the localization

TABLE I
MAIN SPECIFICATIONS OF PCWL-0100 [29]

Range in line-of-sight	About 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

request signal from WiFi devices and extract the information such as IP address. To extract the information, we cannot use encryption such as WEP and WPA-PSK on WiFi communication. We can use transport layer security such as HTTPS.

- 2) Limited resources for localization calculation: The localization CGI program calculates the device location on WiFi AP. Since WiFi APs have limited computational resources, it is difficult to use complex calculation algorithm. We can offload calculation in some part to the JavaScript program working on user devices.

We believe still there is a simple location-based service in which these limitations are insignificant.

IV. EXPERIMENTAL EVALUATION

A. Implementation

To demonstrate the feasibility and to evaluate the basic performances, we implemented our distributed localization system and an example location-based Web service on real WiFi APs. We used WiFi APs PCWL-0100 (PCWL) from PicoCELA Inc [29]. Table I shows the main specifications of the PCWL. The PCWL is a WiFi AP having 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 embedded Linux running on the PCWL.

We installed a lightweight open source Web server `thttpd` [30] on all WiFi APs. The localization CGI program is implemented as a C program. To calculate the location of user devices, we used a simple triangulation algorithm with the propagation model suggested by ITU-R [31] since we don't aim at high accuracy. As for the communication between the CGI program and the RSSI reception server, we used shared memory for simplicity.

The RSSI detection server and the RSSI reception server are also implemented as C programs. The RSSI detection server captures all WiFi frames on a monitor mode interface via `MadWifi` driver. The RSSI detection server then analyzes WiFi frames with `Radiotap` header and extract RSSI, a source IP address, a sequence number, and a destination IP address to generate RSSI-data. The RSSI-data is sent to the RSSI reception server using TCP/IP communication.



Fig. 5. PCWLs installed on the ceiling and the wall.



Fig. 6. Example location-based service. Google Chrome on iPad as showing an indoor map as well as the user location.

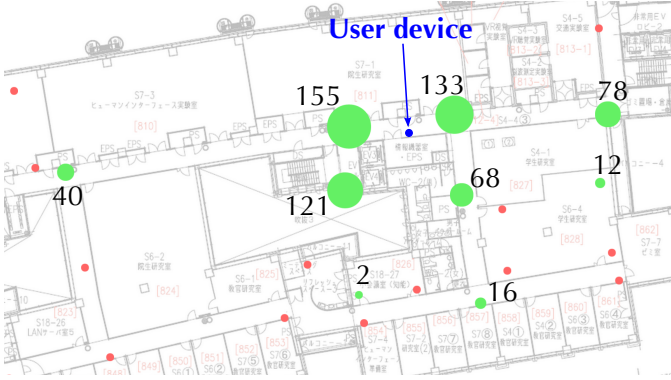


Fig. 7. Number of RSSI-data transmissions on each WiFi AP. Diameter of green circles describes the number of transmissions, while red circles mean no transmission. The numbers beside green circles are the actual number of transmissions.

B. Experiment Environment

We conducted experiments in our university building. We installed 30 PCWLs, i.e. WiFi APs, on the ceiling and the wall in our university building as shown in Fig. 5 and implemented an indoor map Web service which tells the user location. Figure 6 shows our example location-based service. In Fig. 6, a blue circle depicts the location of a user device and red circles depict WiFi APs.

We put a laptop with a WiFi module and access our location-based service Web page using Web browser Google Chrome. We collected logs on three servers in terms of communication and localization calculation for about 20 minutes. The location updater JavaScript is configured to send localization request every 10 seconds. We observed localization calculation for 125 times in total.

C. Number of RSSI-Data Transmissions

To confirm that the APs close to the user device detect the location request signal, we evaluated the number of RSSI-data

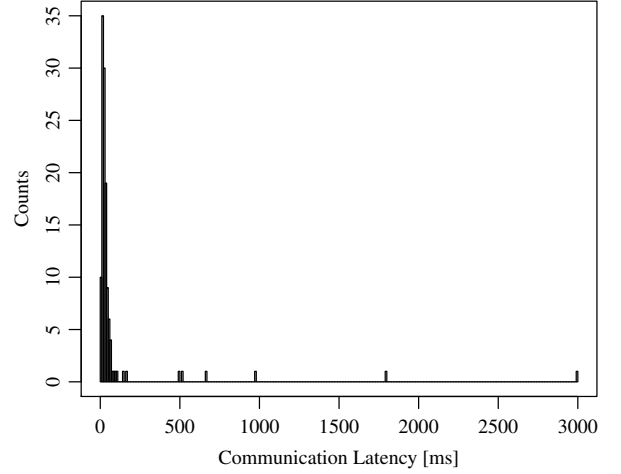


Fig. 8. Histogram of communication latency for RSSI-data collection.

transmissions through the experiment. The number of RSSI-data transmissions equals to the number of location requests detected on WiFi APs.

Figure 7 shows the number of RSSI-data transmissions on each WiFi AP. Each circle describes the location of the WiFi AP. Green circles mean that there is at least one RSSI-data transmission, while red circles mean no transmission. The numbers beside the green circles are the number of transmissions and the diameter of the green circles visually describes the number of transmissions. We note that the user device is associated with the AP that transmits RSSI-data for 133 times. Figure 7 shows the following:

- 1) The WiFi APs close to the user device detect more number of signals. These neighboring APs have higher probability of signal detection than the APs far from the user device since the neighboring APs receive higher power signal.
- 2) On some APs, the number of transmissions is more than the number of localization calculation of 125 times. This is because there are some retransmissions in the TCP layer and the IEEE 802.11 MAC layer.
- 3) There is a case that the WiFi AP far from the user device detects the location request signal. In our experiment, the distance between the user device and the farthest AP that transmits RSSI-data is about 30 meters. Since the farthest AP and the device is in line-of-sight distance, the farthest AP sometimes detects WiFi signal from the user device.

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

D. Communication Latency for RSSI-Data Collection

To determine the wait duration in a localization CGI program described in Section III-C, we evaluated communication latency for RSSI-data collection. The communication latency is defined as a time length from the first reception of RSSI-data to the last reception in the RSSI reception server. In this definition, we ignore the time from a localization Web

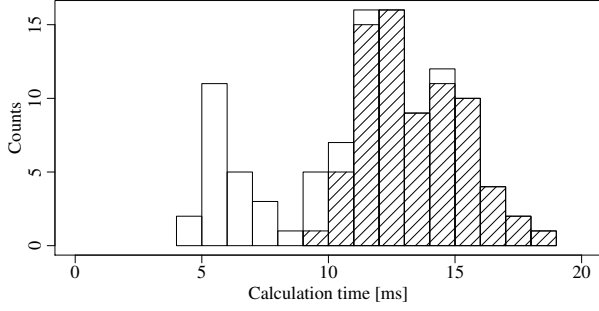


Fig. 9. Histogram of calculation latency for localization. Shadow bar describes calculation latency for successful localizations.

request to the first reception of RSSI-data. This definition is still valuable since the RSSI reception server immediately receives RSSI-data from the RSSI detection server in the same AP.

Figure 8 shows the histogram of communication latency for RSSI-data collection. The mean communication latency is 88.8 milliseconds and the maximum communication latency is 2999.7 milliseconds. The minimum communication latency is 0, which is the case that only one RSSI-data is received. Figure 8 shows the following:

- 1) More than 95 % of RSSI-data collections are completed within 200 milliseconds. Only the APs within few hops from the associated AP send RSSI-data, which results in small communication latency.
- 2) Communication latency sometimes becomes more than 500 milliseconds because PCWLs construct a network path on first data transfer, which sometimes takes few seconds.

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

E. Calculation Latency for Localization

The 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 localization latency, we evaluated calculation latency for localization.

Figure 9 shows the histogram of calculation latency for localization. The shadow bar describes the calculation latency for successful localizations. The calculation sometimes fails since the number of RSSI-data is not enough for triangulation. Figure 9 shows the following:

- 1) Unsuccessful localizations complete in shorter time than successful localizations. This is because the localization CGI program finds it impossible to calculate the location in early stage of the calculation. The calculation fails with insufficient number of RSSI-data.

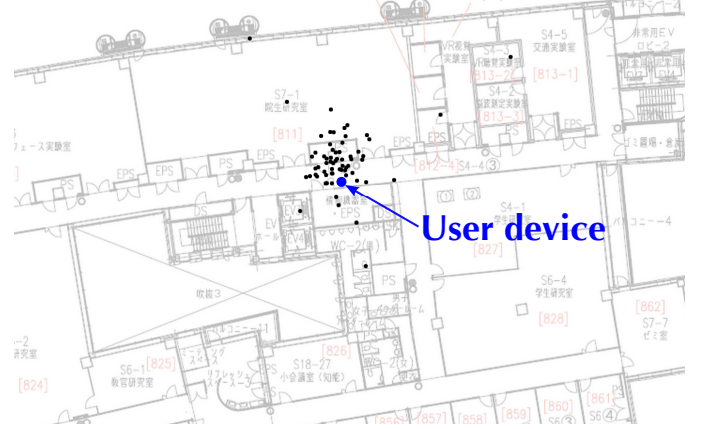


Fig. 10. Localization results.

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

- 2) There is some case that the unsuccessful localization takes more than 14 milliseconds. The calculation sometimes diverges because of the variations of RSSI caused by multi-paths and measurement errors.

The above results reveal that the all calculation completes within 20 milliseconds. Maximum localization latency is therefore 220 milliseconds.

F. Localization Error

Although we don't aim at high accuracy, we evaluated localization error to show that our system can provide location-based services. Figure 10 shows the localization results. Figure 10 shows the following:

- 1) Our system can show the approximate location of the user device. The mean localization error is 4.8 meters.
- 2) There is sometimes considerable localization error. This is mainly because we employ simple triangulation. As described in Section II-C, there are numerous works on accuracy improvement. Some of these works are helpful to improve accuracy.

V. SIMULATION

In our experiment, we cannot monitor forwarding traffic due to the limitation of PCWLs. To demonstrate the effectiveness of our distributed localization system in terms of network traffic, we performed network simulation using ns-3 [32].

A. Simulation Environment

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

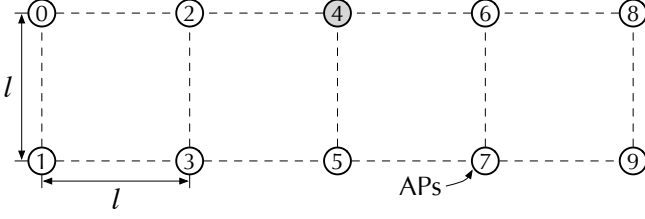


Fig. 11. Arrangement of WiFi APs. Dotted lines indicate network paths. In a centralized system, we assume that an AP 4 is a core AP.

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

We arranged 10 WiFi APs as a 2×5 grid with 50-meter spacing, shown in Fig. 11 with $l = 50$ [m]. WiFi devices are uniformly distributed and move 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 1000 simulation trials for each number of WiFi devices. Each device transmits a localization request signal via an access network every second to the AP associated with the device. The WiFi APs that detect the localization request signal generate RSSI-data and transfer the RSSI-data to the associated AP. The RSSI-data is transferred via UDP/IP communication instead of TCP/IP to exclude the effect of ACKs and retransmissions. We used RSSI-data of 11 bytes, the same data size as our experiment. Each trial simulated 30-second communication. For other configurations, we used default values defined in ns-3.

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

- 1) Distributed system (proposed)

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

- 2) Centralized system

The centralized system is a localization system using a normal AWPN described in Section II-A. In the centralized system, location-based service is implemented on a single Web server connected to a core AP. Each AP measures RSSI of the WiFi device and transfers RSSI-data to the Web server. The core AP is AP 4 in Fig. 11.

B. Network Traffic

We define network traffic as a total transferred data size per one second. Network traffic is therefore calculated by

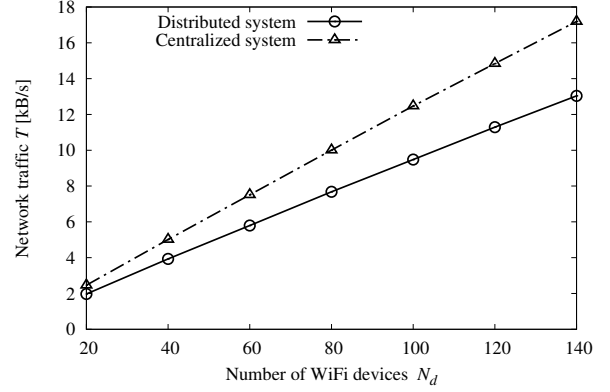


Fig. 12. Network traffic T as a function of the number of WiFi devices N_d .

summing up transmission data size and forwarding data size over all APs. We calculated the network traffic for every trial and averaged out the network traffic.

Figure 12 shows the network traffic as a function of the number of WiFi devices. Figure 12 shows the following:

- 1) Network traffic is approximately proportional to the number of devices in both the distributed system and the centralized system.
- 2) Network traffic in the distributed system is less than that in the centralized system. The network traffic is reduced by about 20.0 % at $N_d = 20$ and 24.1 % at $N_d = 140$. Forwarding traffic in the distributed system is less than that in the centralized system, which results in large decrease in network traffic.

The above simulation results reveal that our distributed system exhibits less network traffic.

C. AP traffic

As described in Section II-B, congestion in the network results in localization latency. To show that our localization system can avoid concentration of traffic on some APs, we evaluated the maximum AP traffic. The AP traffic is defined as data size transmitted by one AP per one second.

Figure 13 shows the maximum AP traffic as a function of the number of WiFi devices. The maximum AP traffic in our distributed localization system is about 60 % of that in the centralized system. This is because traffic does not concentrate on one AP in our distributed localization system, while traffic on a core AP is significant in the centralized system.

The above simulation results reveal that our system distributes traffic over the network.

VI. CONCLUSION

In this paper, we presented a distributed localization system on the WiFi ad-hoc wireless positioning network (AWPN) to realize on-demand location-based services. Toward the goal of *on-demand*, we tackled two challenges: reduction in the installation cost of user applications and reduction in network traffic. We realize an on-demand location-based service as a Web service that can be used via Web browsers, which

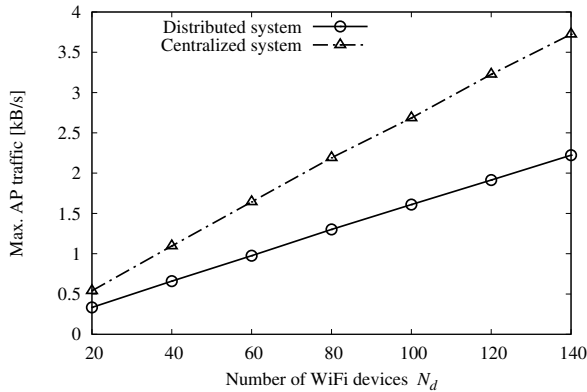


Fig. 13. Maximum AP traffic as a function of the number of WiFi devices N_d .

makes us free from the installation of user applications. With Web servers installed on all WiFi APs, our localization system reduces network traffic by reducing forwarding traffic. We implemented our localization system on real WiFi APs and conduct experimental evaluations. The evaluation results reveal that our system can localize a user device within 220 milliseconds. By performing simulations, we also showed that our distributed localization system can reduce the network traffic by up to 24 % compared to that in the centralized localization system.

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