

Wireless Backhaul Technology in Wireless Sensor Networks: Basic Framework and Applications



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1 Introduction

Sensing equipment has decreased significantly in cost and has spread rapidly in this decade, even though its measurement accuracy and communication performance have improved. Consequently, wireless sensing systems have been widely studied and developed. Setting up a wireless sensor network (WSN) in a wide area requires installing large amounts of wireless communication equipment, viz., sensor gateways, and the installation costs tend to be high, depending on the extension of the sensing area.

Similar problems are occurring in setting up Wi-Fi networks. Currently, the importance of traffic off-loading from cellular networks to Wi-Fi networks is increasing owing to the rapid growth of network traffic [1] caused by the proliferation of smartphones and tablet devices. To extend Wi-Fi coverage areas, a significant number of Wi-Fi access points (APs) are being installed in urban areas. However, installation and maintenance costs become high, depending on the increase in the number of APs. To assist in alleviating this concern, we developed a

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wireless AP that uses wireless backhaul technology. We expect that this technology can alleviate the problems related to setting up wide wireless sensing areas. This article considers how wireless backhaul technology can be used in WSNs.

The remainder of this article is organized as follows. Section 2 briefly describes related technologies. Section 3 describes our basic sensing framework utilizing wireless backhaul technology. In Sect. 4, applications working in this framework are shown. Section 5 presents our concluding remarks.

2 Related Technologies

2.1 WSNs and Sensor and Actuator Networks (SANs)

A sensor network is a framework for observing the surrounding environment, e.g., temperature, illuminance, and noise, in a particular area. A typical sensor network consists of sensor nodes, sensor gateways, database servers, and access networks. Each sensor node is used to collect surrounding environmental data and transmit them to database servers. Sensor gateways are located in the same network as database servers and aggregate communication between sensor nodes and database servers.

WSNs are sensor networks that partially or fully use wireless communication technology. In some WSNs, sensor nodes can relay data transmitted from other nodes. Wi-Fi, Bluetooth, Bluetooth low energy, and LoRa technologies are often used in the infrastructures of WSNs. Wi-Fi is standardized as the IEEE 802.11 series [2] and is certified to have interoperability by the Wi-Fi alliance [3]. Most commoditized wireless access points (APs) use Wi-Fi technology. Bluetooth [4] is a technology for exchanging data over short distances (less than 10 m) and is standardized as IEEE 802.15.1 [5]. Bluetooth low energy (Bluetooth LE, BLE) is a type of Bluetooth technology that has low power consumption, data rate (in the range of 10 kbps), and latency (ms). LoRa (LoRaWAN) [6] is a wireless communication technology for an Internet of Things network and is standardized as IEEE 802.15.4 g. LoRa has a long communication distance (km) and low data rate (kbps).

A SAN is a combined framework consisting of a sensor network, data analysis functionalities, and actuators. Data analysis functionalities provide several kinds of analysis results, e.g., statistical calculation, forecasting, and situation recognition, on the basis of gathered sensor data. Actuators take appropriate actions with regard to the surrounding environment, e.g., lighting adjustment and airflow control, depending on the analysis results. Using machine learning algorithms in a SAN can provide more appropriate and natural actuation after a specific duration of continuous operation.

2.2 Wireless Backhaul Technology

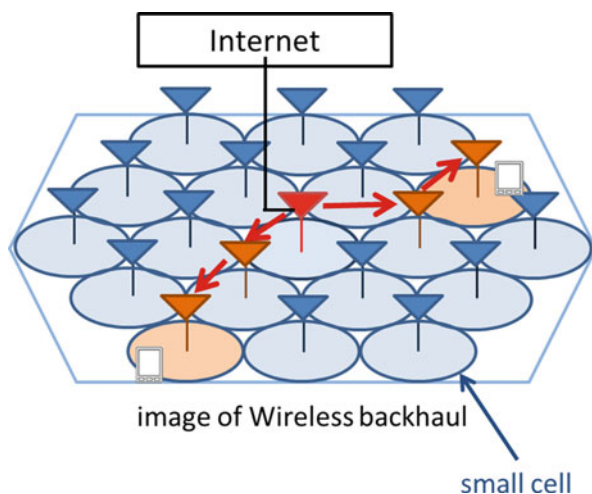
Small cells are the key technology in setting up a wide Wi-Fi coverage area and achieving a large network capacity. To connect small cells to the core network (e.g., Internet), backhaul is essential. However, wired backhaul method is uneconomical and convenient, because all APs are wired to the core network. And achieving wide Wi-Fi coverage areas requires installing huge numbers of cables.

Wireless backhaul is a wireless multi-hop network in which APs are linked wirelessly with the capability of relaying packets. In a wireless backhaul network, a few APs (we refer to them as core nodes) are wired to the core network and serve as gateways connecting the wireless multi-hop network to the Internet. Therefore, wireless backhaul is advantageous in achieving a wide Wi-Fi coverage area, because this technology can reduce wiring cost significantly. For example, as in Fig. 1, the Wi-Fi coverage area can be set up by placing wireless APs with only one AP wired to the core network. However, mobile devices in this area can access the Internet, regardless of the AP with which a device is associated.

2.3 PCWL-0200

PCWL-0200 [7] is a wireless local area network (LAN) AP developed in our laboratory that uses wireless backhaul technology. This AP can set up a Wi-Fi coverage area without manually configuring frame relay routes among APs; the route is determined autonomously on the basis of the radio wave propagation environment, e.g., the received signal strength indications observed between each two APs. PCWL-0200 has been commercialized, and a significant number of Wi-Fi

Fig. 1 Introduction of wireless backhaul network. This technology enables extending a large Wi-Fi coverage area without laying huge numbers of access cables; only one AP is required to be wired to the core network



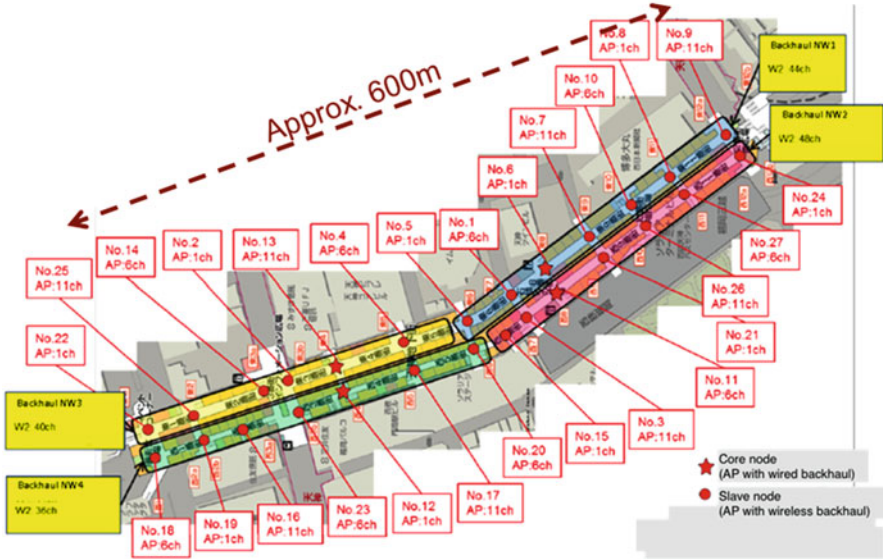


Fig. 2 Actual Wi-Fi access area set up using our Wi-Fi APs PCWL-0200; the length of the area is approximately 600 m, with only four APs wired to the core network

access areas set up using the APs are in practical use. Figure 2 shows an example of an approximately 600 m-long Wi-Fi access area using our Wi-Fi AP [8]. This Wi-Fi area is capable of accepting 4000 distinct users in a day, even though only four APs are wired to the core network.

Another feature of PCWL-0200 is that this AP can configure frame relay routes among the APs dynamically. By periodically reconfiguring a relay route, these APs can maintain a relay route with a specific level of communication quality and performance. This feature is suitable for mobile APs, e.g., APs located on moving vehicles, for comprising a wireless network, because this AP can reconfigure relay routes according to the locational changes of an AP.

3 Wireless Backhaul Network and WSNs

Our wireless AP PCWL-0200 can set up wide Wi-Fi access areas installing only a few access cables. This AP is also capable of connecting with a wired LAN device and serving as a gateway connecting the device to a wireless backhaul network. Owing to this feature, sensor gateways equipped with LAN connectors can transfer data to networked servers through a wireless backhaul network by wiring sensor gateways to slave APs simply. Note that connections between sensor nodes and gateways can be established using any optional technology. Data from sensor

nodes are transmitted to a networked server via a wireless backhaul network; the AP referred to as the core serves as a gateway to connect this wireless network to the core network. Introducing wireless backhaul technology into WSNs leaves communications among sensor gateways unwired; this can reduce installation and maintenance costs of WSNs.

Figure 3 shows the components of an example WSN that uses wireless backhaul technology. PCWL-0200s are used to set up a wireless access infrastructure. Each sensor gateway is connected to the nearest adjacent slave AP and transmits data from sensor nodes to the networked server via the wireless backhaul network. Data communications among slave APs and between slave APs and the core AP are performed wirelessly; each slave AP is wired only to a sensor gateway with considerably fewer cables than in ordinary WSNs. In this framework, the core AP is wired to the core network, and sensor data are stored in the networked server. In the event that a WSN uses a local server, the core AP is wired only to the server.

The functionality of this WSN can be enhanced by connecting several types of servers to the database. For example, sensing results can be displayed visually using a web browser by connecting a web server to the database. To set up a SAN on this framework, a data analysis server and a control server for operating several types of actuators, e.g., cylinders and motors, are combined with this WSN. In the event that the system handles huge amounts of analysis data, high-performance servers and large-capacity databases for data analysis can be used in this sensing framework.

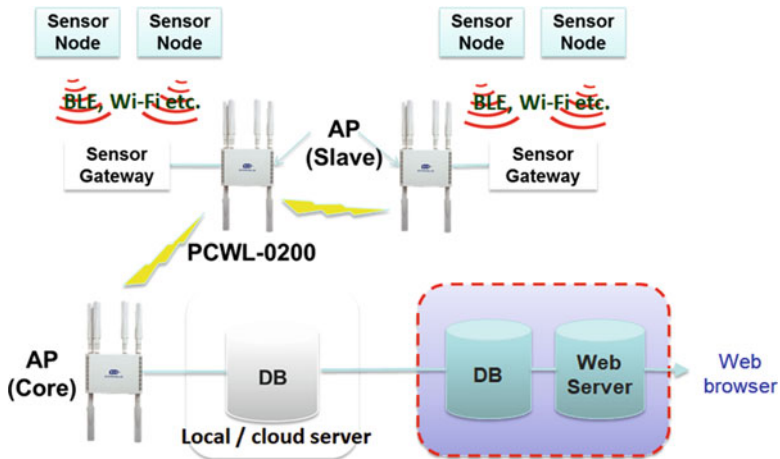


Fig. 3 Example WSN with wireless backhaul technology. Each sensor gateway is wired to the AP and relays sensing data gathered from surrounding sensor nodes to a server connected to the AP via a wireless backhaul network

3.1 Sensor Data Visualization Framework

We developed a sensor data visualization framework in this WSN framework. Figure 4 shows an example of the visualized temperature data in a laboratory room. In this figure, the respective circles indicate the locations of sensor nodes, and each square indicates the location of a sensor gateway. The sensing area is divided into a $0.2\text{ m} \times 0.2\text{ m}$ grid, each unit of which is colored according to a sensor measurement as indicated in the legend shown at the bottom; higher values are indicated by red, and lower values are indicated by blue. This visualization framework uses a simple interpolation technique to estimate the environment of a particular sensing area from spatially sparse data. The environment of a particular sensing area can be recognized visually.

Our visualization framework can also show the time-series trend of each sensor node measurement. Figure 5 shows an example of a time-series plot. The horizontal axis corresponds to measuring times, and the vertical axis corresponds to measured values. Each dot is colored in the same manner as in the case of the room environment visualization.

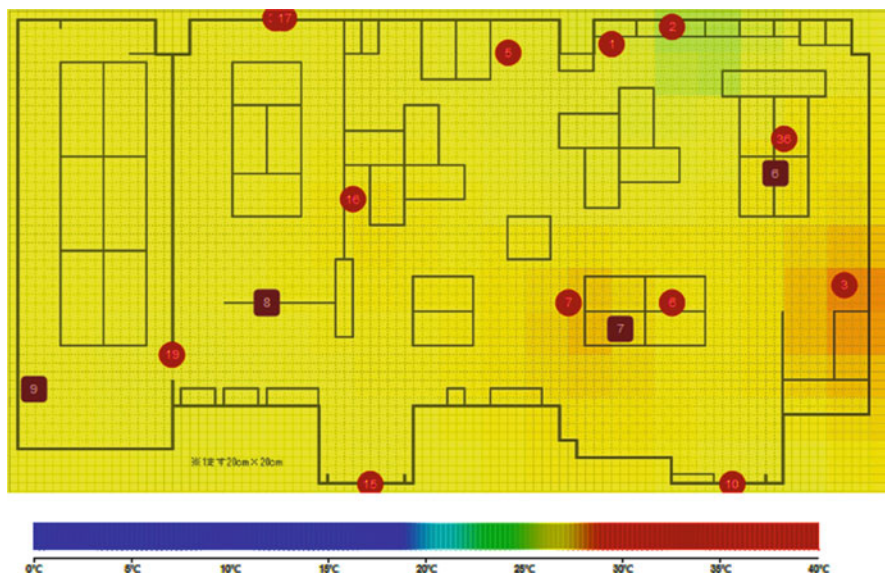


Fig. 4 Example of sensor data visualization. This figure shows the temperature environment of a particular room. Each circle indicates the location of a sensor node, and each square indicates the location of a sensor gateway

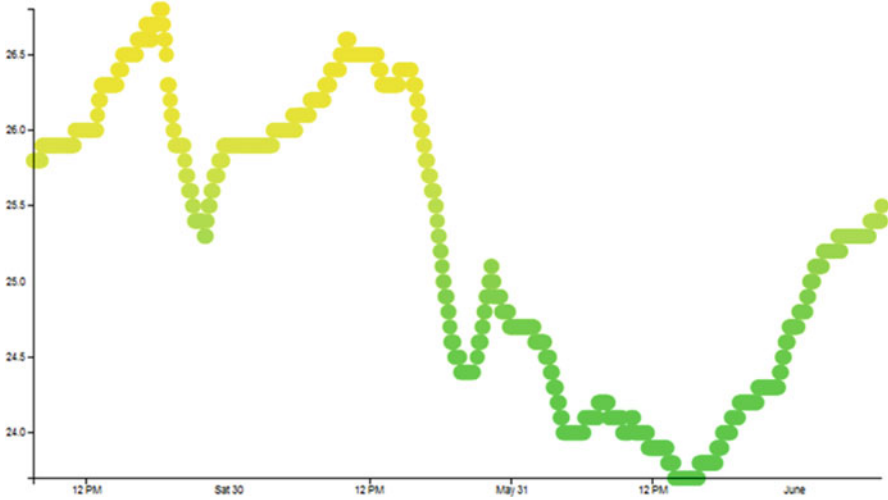


Fig. 5 Example of a time-series plot. Each dot is colored according to its measurement value

4 Applications of Wireless Backhaul Sensor Networks

This section introduces four applications using wireless backhaul sensor networks, a ubiquitous camera network, a Wi-Fi tag tracking system, a criminal fishing system, and a networked vehicle.

4.1 Ubiquitous Camera Network

A wireless camera network can be set up by connecting network cameras to slave APs. We refer to this framework as a ubiquitous camera network. Figure 6 shows the components of such a network. Each single-board computer with a universal serial bus (USB) camera is wired to a slave AP. Several types of information can be obtained by analyzing the camera images shot in the vicinity of the cameras and stored in the database.

However, transmission of many high-resolution images consumes sufficient wireless network bandwidth to degrade communication quality, e.g., to increase packet loss and network delay. To alleviate this problem, we considered analyzing camera images using single-board computers and transmitting only the analysis results. TensorFlow [9] is used in the ubiquitous camera network to analyze camera images. Inception-v3 [10], an image recognition model that works on TensorFlow, can recognize what is photographed in a particular picture and enumerate it as textual information. Recognition results (we refer to them as spatial textual information) are shown as five candidate synsets registered in WordNet [11] with

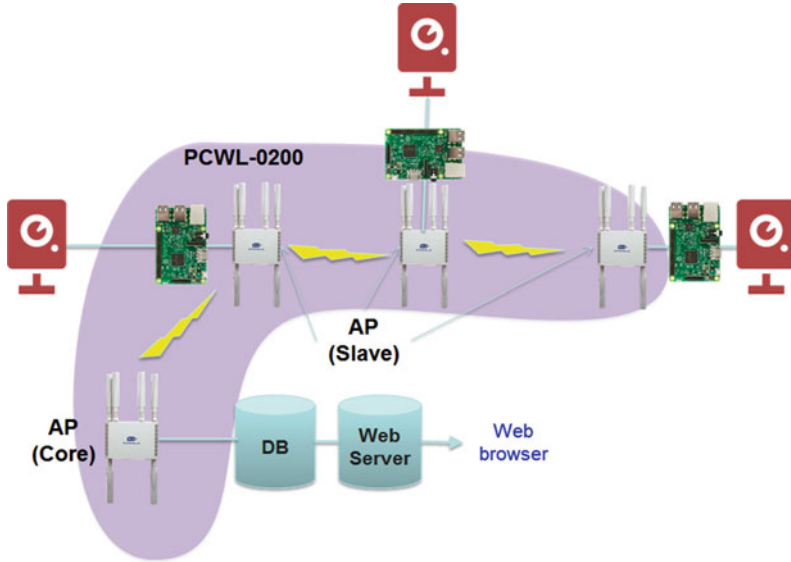


Fig. 6 Example of a ubiquitous camera network. Each single-board computer with a USB camera is wired to a slave AP. Spatial textual information is transmitted to a server connected to the AP referred to as the core via wireless backhaul network

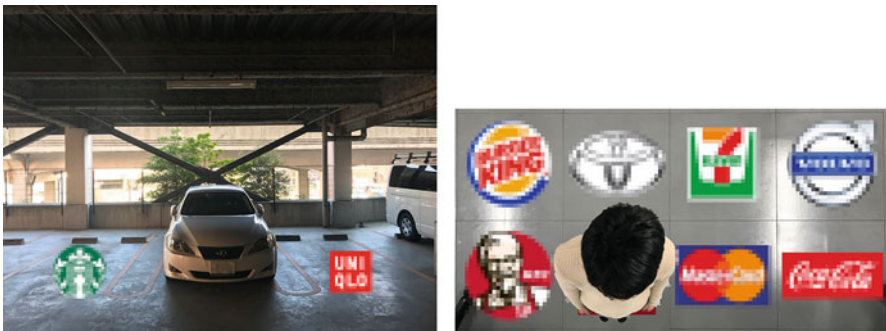


Fig. 7 Applications of spatial textual information. Left: vacancy of a parking area can be recognized in an image by printing logos on each parking space. Right: vehicle congestion can be recognized by printing logos on vehicle floors

a confidential score on each synset. In the ubiquitous camera network, each single-board computer executes TensorFlow and transmits spatial textual information to the database server. Generally, the data size of a still image is measured in megabytes, and spatial textual information measures less than 1 KB.

Through the use of spatial textual information, occupancy and vacancy of a particular region can be recognized by observing the region visually. For example, in Fig. 7, the vacancy of a parking area can be recognized by printing logos, i.e.,

pictures easy to distinguish from each other, on each parking spot and monitoring the area. When the logo can be recognized, the parking spot is vacant. In the same manner, congestion on each train vehicle can be observed by printing logos on the floor and observing the floor through captured images; when many logos can be recognized, the vehicle is less crowded.

4.2 Wi-Fi Tag Tracking System

Demand for care services, especially for children and the elderly, has been increasing. Several Global Positioning System (GPS)-based pedestrian tracking systems are being investigated and developed [12, 13], but GPS cannot provide accurate position estimates in high-rise areas and indoor environments. To alleviate this issue, we propose a pedestrian tracking system that uses Wi-Fi beacons held by target persons and Wi-Fi APs placed widely and densely in a specified area. The proposed tag tracking system uses probe request signals broadcast by mobile devices to estimate their positions. Our pedestrian tracking system uses Wi-Fi APs to set up a positioning area and Wi-Fi beacons that broadcast probe request signals periodically. Each beacon's position, i.e., target user's position, in this area is estimated using a networked server, on the basis of the probe request signals broadcast by the beacons and captured by the APs. The position estimates are stored in a networked database. The trajectories of each beacon are estimated on the basis of the position estimates, taking the floor plan of the area into account.

The system components are shown in Fig. 8. Each target user holds a Wi-Fi beacon. PCWL-0200s are used to set up a Wi-Fi coverage area, i.e., a positioning area, and capture the probe request signals broadcast by surrounding beacons. These APs transmit these signals to a positioning server implemented in Python via the wireless backhaul network at the request of the server. A single probe request signal can be captured on multiple APs. Each beacon's position is estimated on the positioning server through analysis of these signals. Position estimates are stored in a MongoDB [14] positioning database. The trajectory of each beacon is estimated from its position estimates and stored on the positioning server. These trajectories are displayed visually using the D3.js [15] JavaScript library. The web server is implemented using Django [16].

Figure 9 shows a screenshot of the proposed pedestrian tracking system. The main panel (Panel 1) displays the estimated trajectory of each Wi-Fi beacon. The filled numbered circles indicate the locations of the respective APs, and the respective arrows and unfilled circles, colored as shown in the legend, indicate the estimated trajectories of individual beacons. The arrows indicate the route each beacon has traveled for a specific duration, and the unfilled circles indicate locations at which the beacon has remained. In Fig. 9, Beacon 1 (blue) has remained near AP12, and Beacon 3 (green) has traveled from AP7 to AP5. This panel also has functionalities to show the floor on which each beacon is located and to change the

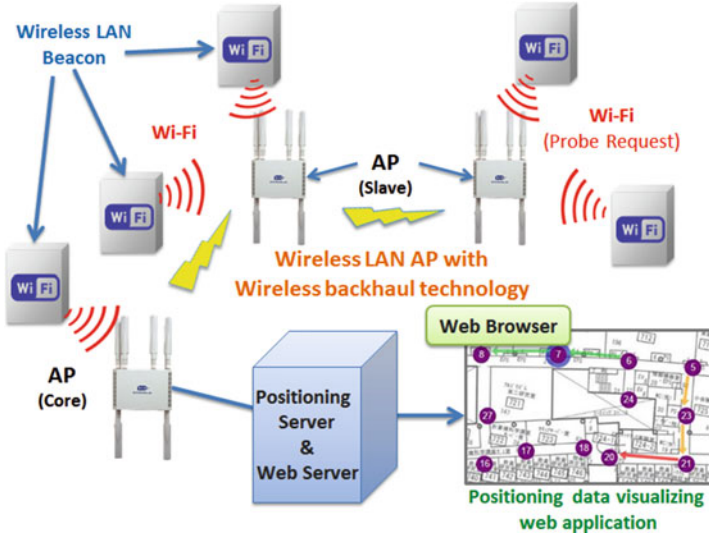


Fig. 8 Components of the tag tracking system. Each beacon’s position is estimated on the positioning server by analyzing the probe request signals captured by wireless APs. Probe request signals are gathered to the server via the wireless backhaul network

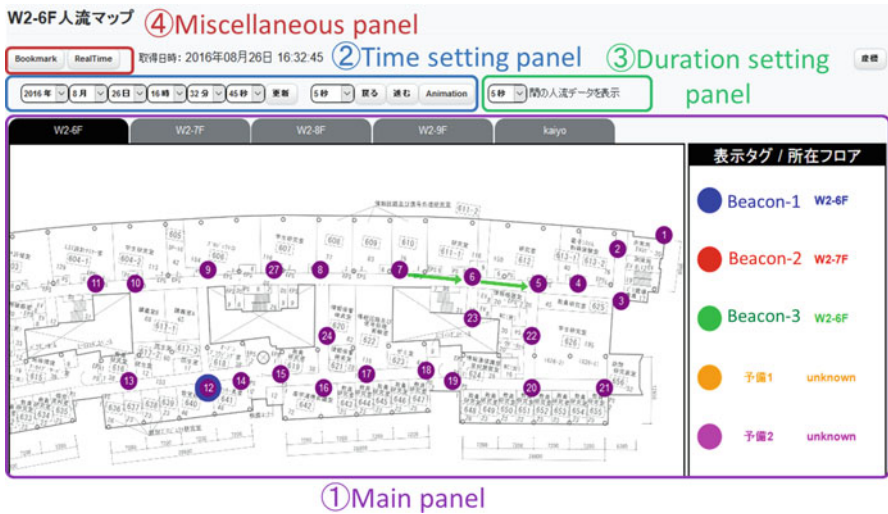


Fig. 9 Screenshot of the pedestrian tracking system. The arrows and unfilled circles colored as shown in the legend indicate the estimated positions of respective beacons

floor to display estimated trajectories. The floor on which each device is located is displayed in the right-hand table of the main panel. This table also indicates the names of users who hold Wi-Fi beacons.

4.3 Criminal Fishing System

Criminal activities, such as graffiti, shoplifting, larceny, and kidnapping, occur in urban areas, causing various types of social damage. We expect that utilizing large numbers of APs in urban areas as a component of a criminal investigation assistance system can reduce the frequency of criminal activity and improve public safety. The proposed “criminal fishing system” uses a large number of wireless LAN APs and cameras. This system enumerates candidate media access control (MAC) addresses of a culprit’s mobile device from probe request signals gathered by APs during the period in which a culprit remains near the incident scene.

Figure 10 illustrates the components of the system. The principal components are an administrative server, PCWL-0200s (Wi-Fi APs), and USB cameras. Each AP gathers probe request signals and periodically transmits radio wave fingerprints to the administrative server. In this system, we refer to a probe request signal as a radio wave fingerprint, because it contains a MAC address basically unique to a particular network interface. Each AP executes motion, an image-capturing program that captures images when the program recognizes moving objects. These images are transmitted to the administrative server via a wireless backhaul network. The transmitted radio wave fingerprints and images are stored in the database on the server. The administrative server is equipped with a web application for enumerating the candidate MAC addresses of a culprit’s device from a huge amount of stored

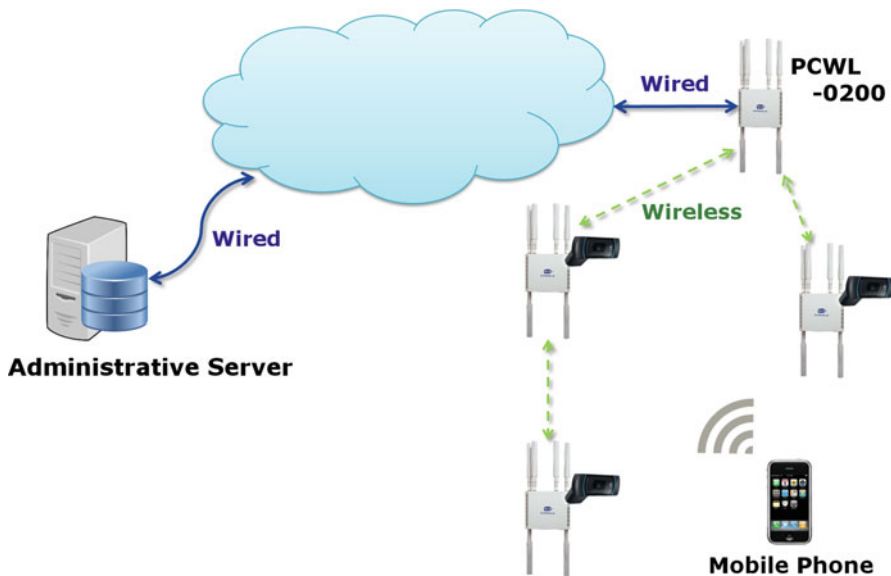
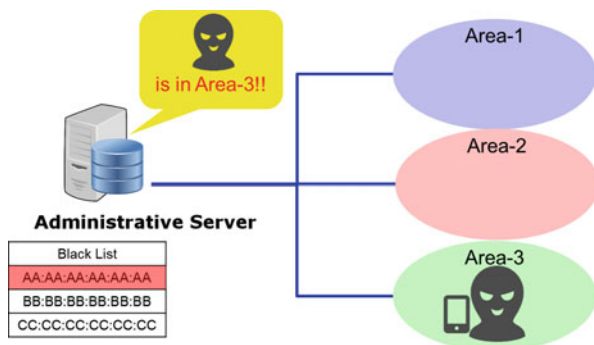


Fig. 10 Criminal fishing system. Each access point gathers probe request signals broadcast by surrounding devices. These signals and photos near each AP are transmitted to the administrative server via a wireless backhaul network

Fig. 11 Example of surveillance assistance using candidate MAC addresses. After candidate MAC addresses are enumerated, the system monitors the appearance of the MAC address. When the culprit's MAC address is observed in one of the investigation areas, the system issues an alert and captures photos around the area



data. A facility administrator uses the web application to determine the duration that the culprit remains near the scene of the incident while checking the stored images. The administrative server enumerates candidate MAC addresses during this time.

Even if the detailed appearance of the culprit cannot be obtained near the scene of the incident, it can be obtained later at another location by surveilling the enumerated MAC addresses, as shown in Fig. 11. When a MAC address is captured in a particular area, the appearance of the device owner can be obtained from the camera image shot near there. The probability of identifying the culprit can be improved by locating APs over wide areas, with high density.

We must consider how our criminal fishing system works if the culprit has a mobile device with a spoofed or randomized MAC address. In short, MAC spoofing and randomization themselves have no critical effect on this system. These technologies sometimes trigger frequent changes of MAC address, which undeniably affect the criminal fishing system. In the case in which a MAC address is changed very frequently, e.g., every few minutes, the address cannot be enumerated as one of the candidate MAC addresses. Depending on the frequency of MAC address changes, the criminal fishing system can assist criminal investigation as follows. If the MAC address is not changed for several days (perhaps even several hours), the usual appearance of the owner of the device, i.e., the candidate culprit, can be obtained by monitoring the MAC address. In this manner, the system can assist crime investigations, even if the MAC address has been changed before the candidate culprit is actually questioned regarding the incident. In a case in which the MAC address is rarely changed regardless of whether the address is factory-assigned or spoofed, this MAC address itself can be considered as evidence that the person is a culprit in the incident.

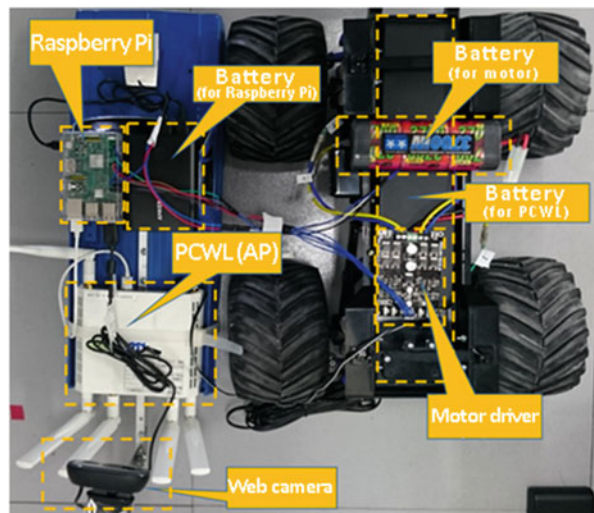
4.4 Networked Vehicle and WSN

As mentioned in Sect. 2.3, a PCWL-0200 AP is capable of configuring frame relay routes among the APs comprising a wireless network autonomously and dynamically. This feature enables a WSN to use networked vehicles equipped with AP functionality and several types of sensors and actuators.

A prototype of the networked vehicle, PicoRover, has been developed based on this concept. The vehicle is shown in Fig. 12. Its principle components are a PCWL-0200 Wi-Fi AP, a Raspberry Pi, a USB camera, and a motor driver integrated circuit. To operate PicoRover, a remote computer sends control commands to the vehicle via a wireless backhaul network. The Raspberry Pi decodes the commands and operates the vehicle using a motor driver, sending camera images to a remote computer via the wireless backhaul network at the user's request.

PicoRover can be enhanced to a networked sensing vehicle by attaching several types of sensors to a Raspberry Pi on the vehicle. Sensing data can be transmitted to a networked server via a wireless backhaul network in the same manner as camera images. Using networked sensing vehicles in a WSN can reduce the number of sensor nodes significantly. The total installation cost of sensor nodes can be reduced, even though the installation cost of a network sensing vehicle is estimated to be higher than that of ordinary sensor nodes. Maintenance costs of sensor nodes can also be reduced by introducing networked sensing vehicles, since the total number of sensor nodes is reduced. Another feature of such a vehicle is that the sensing area of a WSN can be formed dynamically and flexibly using these vehicles, since the vehicles are capable of configuring frame relay routes among themselves autonomously and dynamically. For example, in Fig. 13, the sensing area is formed by driving each sensing vehicle remotely, owing to the functionality of the PCWL-

Fig. 12 PicoRover. This vehicle is equipped with a PCWL-0200 and works as a moving AP. Control commands are sent to the vehicle via a wireless backhaul network. A Raspberry Pi decodes the commands and operates the vehicle, which is equipped with a USB camera whose images are transmitted to a remote computer



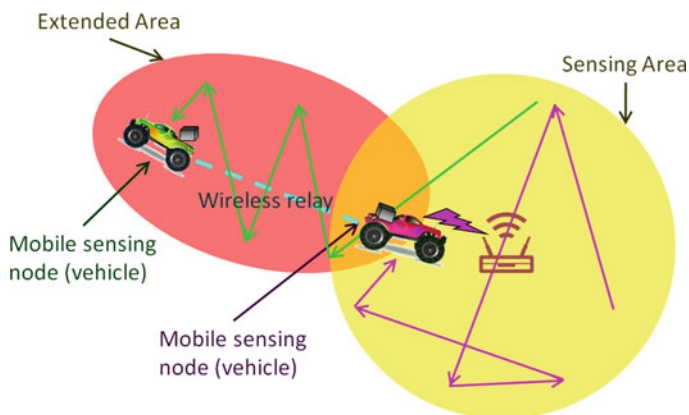


Fig. 13 Extension of sensing area using networked sensing vehicles. The sensing area can be extended and adjusted by driving these vehicles. Frame relay routes among sensing vehicles are configured autonomously and dynamically, and control commands and sensing data are exchanged using a wireless backhaul network

0200 AP. In this manner, the sensing area can be extended to locations that ordinary WSNs find difficult to cover, e.g., where access cables are difficult to lay, where sensor gateways and nodes cannot be placed permanently, or where persons have difficulty entering the region.

To measure the environment of a particular area continuously and autonomously, a sensing vehicle must be equipped with the functionality of inspecting the area and measuring the surrounding environment autonomously. The measurement frequency at a location, i.e., the frequency of passing vehicles, can be adjusted by changing the number of sensing vehicles and their inspection routes.

Introducing networked sensing vehicles in a WSN also enables on-demand sensing. Users of this sensing framework can obtain environmental information anytime and anywhere at the request of the user. In an ordinary WSN, it is difficult to satisfy this kind of demand; measuring the environment of a specific location requires that a person go there and place sensors in advance. Using networked sensing vehicles in WSNs can eliminate this preparation. Switching between autonomous and on-demand sensing can be expected to increase the usability of the vehicle. Coexistence of multiple sensing methods will be a unique characteristic of a WSN with networked sensing vehicles.

5 Conclusion

This paper described the introduction of wireless backhaul technology into WSNs. Doing this unwires communication among sensor gateways. Because communication between sensor nodes and gateways can be established with any optional

technology, it is easy to replace the network infrastructure of existing WSNs. Installation and maintenance costs of WSNs can be reduced by using this technology, since the number of access cables is reduced significantly.

Four application systems based on this sensing framework were described, a ubiquitous camera network, a Wi-Fi tag tracking system, a criminal fishing system, and a networked vehicle. Using networked vehicles in a sensor network can reduce the number of sensor nodes significantly. The total installation and maintenance cost of sensor nodes can be reduced, even though the installation cost of a networked sensing vehicle is estimated to be much higher than that of an ordinary sensor node. Moreover, using a networked sensing vehicle is also beneficial because a user of this sensing framework can measure environmental information anytime and anywhere at the request of the user.

This sensing framework has the potential to be used with many types of sensing systems, because any kind of sensing equipment can be used with it. We would like to conduct further investigations aiming at the discovery of further application scenarios, and we expect to report novel sensing applications on other occasions.

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