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LOCATION DETERMINATION OF A DEVICE BASED ON DIRECTIONAL INFORMATION OF SIGNALS

Abstract

Techniques describe a network management system comprising a memory and processing circuitry configured to obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location and a target device relative to the at least one reference device positioned at an unknown location. The processing circuitry may further be configured to obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device. The processing circuitry may further be configured to determine, based on the distance measurements and the directional information, a plurality of possible positions of the target device relative to the at least one reference device. The processing circuitry may further be configured to determine, based on the directional information, a candidate position from the plurality of possible positions.

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Background/Summary

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/554,409, filed 16 Feb. 2024, the entire contents of which is incorporated herein by reference.

TECHNICAL FIELD

[0002] The disclosure relates generally to computer networks and, more specifically, to monitoring and troubleshooting computer networks.

BACKGROUND

[0003] Commercial premises or sites, such as offices, hospitals, airports, stadiums, or retail outlets, often install complex wireless network systems, including a network of wireless access points (APs), throughout the premises to provide wireless network services to one or more wireless client devices (or simply, "clients"). APs are physical, electronic devices that enable other devices to wirelessly connect to a wired network using various wireless networking protocols and technologies, such as wireless local area networking protocols conforming to one or more of the IEEE 802.11 standards (i.e., "WiFi"), Bluetooth/Bluetooth Low Energy (BLE), mesh networking protocols such as ZigBee or other wireless networking technologies. Many different types of wireless client devices, such as laptop computers, smartphones, tablets, wearable devices, appliances, and Internet of Things (IoT) devices, incorporate wireless communication technology and can be configured to connect to wireless access points when the device is in range of a compatible wireless access point in order to access a wired network. In the case of a client device running a cloud-based application, such as voice over Internet Protocol (VOIP) applications, streaming video applications, gaming applications, or video conference applications, data is exchanged during an application session from the client device through one or more APs and one or more wired network devices, e.g., switches, routers, and/or gateway devices, to reach the cloud-based application server.

SUMMARY

[0004] In general, this disclosure describes one or more techniques for determining a location of devices at a site based on directional information of signals. For example, a network management system configured to manage wireless networks at a site may determine a location (e.g., a relative distance between devices) and/or orientation (e.g., a rotational position of devices) of devices at the site and use such determination to place the devices on a site map used to understand the deployment of devices at the site. A network management system may use, for example, a localization algorithm (e.g., multilateration techniques) to determine the location of a target device based on a determined distance between a target device (e.g., a target access point or target client device) and one or more reference devices (e.g., reference access point(s)). For instance, the network management system may obtain distance measurements (e.g., measurements determined based on a fine timing measurements protocol) between at least one reference device and the target device based on one or more wireless signals exchanged between the at least one reference device and the target device and determine a location of the target device at the site based on the distance measurements. However, determining the location of the target device based simply on distance measurements may produce ambiguous results, such as when a target device is determined to be in two or more possible locations that are equidistant or near equidistant to the at least one reference device, referred to herein as "flip ambiguity," which may further result in the incorrect placement of the target device on the site map. In addition, environmental interference, scarcity of reference devices, and/or other factors may cause inaccurate distance measurements used to determine the location of the target device.

[0005] The techniques described herein supplement distance measurements used to determine the location of a target device at a site with directional information of signals communicated between at least one reference device and the target device to resolve ambiguities or compensate for inaccurate distance measurements. For example, the network management system may obtain directional information that specifies a direction of one or more signals (e.g., BLUETOOTH Low Energy (BLE) signals, etc.) communicated between an antenna of the at least one reference device and an antenna of the target device. Based on the distance measurements and directional information, the network management system may detect a localization error of one or more devices, such as determining the target device has two or more possible positions. The network management system may determine a candidate position of the target device from the two or more possible positions of the target device based on the directional information. For example, the network management system may determine, based on the directional information specifying a direction of one or more signals between the at least one reference device and the target device, a relative orientation between the at least one reference device and the target device, which may indicate a candidate position of the target device relative to the reference device.

[0006] In one example, the disclosure is directed to a network management system comprising memory and one or more processors in communication with the memory and configured to obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site. The one or more processors may further be configured to obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device. The one or more processors may further be configured to determine, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device. The one or more processors may further be configured to determine, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device.

[0007] In another example, the disclosure is directed to a method comprises obtaining distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site. The method further comprises obtaining directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device. The method further comprises determining, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device. The method further comprises determining, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device.

[0008] In yet another example, the disclosure is directed to non-transitory computer-readable storage media comprising instructions that, when executed, cause one or more processors to obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site. The instructions may further cause the one or more processors to obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device. The instructions may further cause the one or more processors to determine, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device. The instructions

may further cause the one or more processors to determine, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device.
[0009] The details of one or more examples of the techniques of this disclosure are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the techniques will be apparent from the description and drawings, and from the claims.

Description

BRIEF DESCRIPTION OF DRAWINGS
[0010] FIG. **1**A is a block diagram of an example network system including a network management system, in accordance with one or more techniques of the disclosure.
[0011] FIG. **1**B is a block diagram illustrating further example details of the network system of FIG. **1**A.
[0012] FIG. **2** is a block diagram of an example access point device, in accordance with one or more techniques of this disclosure.
[0013] FIG. **3** is a block diagram of an example network management system, in accordance with one or more techniques of the disclosure.
[0014] FIG. **4** is a block diagram of an example user equipment device, in accordance with one or more techniques of this disclosure.
[0015] FIG. **5** is a block diagram of an example network device, such as a router or switch, in accordance with one or more techniques of this disclosure.
[0016] FIG. **6** illustrates an example of determining a location of a target device based on directional information of signals, in accordance with one or more techniques of this disclosure.
[0017] FIG. **7** illustrates an example of determining a location of a target device with limited reference devices based on directional information of signals, in accordance with one or more techniques of this disclosure.
[0018] FIG. **8** illustrates an example of determining a location of a target device with a single reference device based on directional information of signals, in accordance with one or more techniques of this disclosure.
[0019] FIG. **9** is a flow chart illustrating an example operation for localization of devices at a site, in accordance with one or more techniques of this disclosure.
DETAILED DESCRIPTION
[0020] FIG. **1**A is a block diagram of an example network system **100** including network management system (NMS) **130**, in accordance with one or more techniques of this disclosure. Example network system **100** includes a plurality sites **102**A-**102**N at which a network service provider manages one or more wireless networks **106**A-**106**N, respectively. Although in FIG. **1**A each site **102**A-**102**N is shown as including a single wireless network **106**A-**106**N, respectively, in some examples, each site **102**A-**102**N may include multiple wireless networks, and the disclosure is not limited in this respect.
[0021] Each site **102**A-**102**N includes a plurality of network access server (NAS) devices, such as access points (APs) **142**, switches **146**, or routers (not shown). For example, site **102**A includes a plurality of APs **142**A-**1** through **142**A-N (collectively referred to herein as “APs **142**A”). Similarly, site **102**N includes a plurality of APs **142**N-**1** through **142**N-M (collectively referred to herein as “APs **142**N”). Each AP **142** may be any type of wireless access point, including, but not limited to, a commercial or enterprise AP, a router, or any other device that is connected to a wired network and is capable of providing wireless network access to client devices within the site.
[0022] Each site **102**A-**102**N also includes one or more client devices, otherwise known as user equipment devices (UEs), referred to generally as UEs or client devices **148**, representing various

wireless-enabled devices within each site. For example, a plurality of UEs **148**A-**1** through **148**A-N are currently located at site **102**A. Similarly, a plurality of UEs **148**N-**1** through **148**N-M are currently located at site **102**N. Each UE **148** may be any type of wireless client device, including, but not limited to, a mobile device such as a smart phone, tablet or laptop computer, a personal digital assistant (PDA), a wireless terminal, a smart watch, smart ring, or other wearable device. UEs **148** may also include wired client-side devices, e.g., IoT devices such as printers, security devices, environmental sensors, or any other device connected to the wired network and configured to communicate over one or more wireless networks **106**. References to "N" or "M" may represent any number of devices. References to "N" for different elements need not be the same number. Similarly, references to "M" for different elements need not be the same number.

[0023] In order to provide wireless network services to UEs **148** and/or communicate over the wireless networks **106**, APs **142** and the other wired client-side devices at sites **102** are connected, either directly or indirectly, to one or more network devices (e.g., switches, routers, or the like) via physical cables, e.g., Ethernet cables. In the example of FIG. **1**A, site **102**A includes a switch **146**A to which each of APs **142**A-**1** through **142**A-N at site **102**A is connected. Similarly, site **102**N includes a switch **146**N to which each of APs **142**N-**1** through **142**N-M at site **102**N are connected. Although illustrated in FIG. **1**A as if each site **102** includes a single switch **146** and all APs **142** of the given site **102** are connected to the single switch **146**, in other examples, each site **102** may include more or fewer switches and/or routers. In addition, the APs and the other wired client-side devices of the given site may be connected to two or more switches and/or routers. In addition, two or more switches at a site may be connected to each other and/or connected to two or more routers, e.g., via a mesh or partial mesh topology in a hub-and-spoke architecture. In some examples, interconnected switches and routers comprise wired local area networks (LANs) at sites **102** hosting wireless networks **106**.

[0024] Example network system **100** also includes various networking components for providing networking services within the wired network including, as examples, an Authentication, Authorization and Accounting (AAA) server **110** for authenticating users and/or UEs **148**, a Dynamic Host Configuration Protocol (DHCP) server **116** for dynamically assigning network addresses (e.g., IP addresses) to UEs **148** upon authentication, a Domain Name System (DNS) server **122** for resolving domain names into network addresses, a plurality of servers **128**A-**128**N (collectively "servers **128**") (e.g., web servers, databases servers, file servers and the like), and a network management system (NMS) **130**. As shown in FIG. **1**A, the various devices and systems of network **100** are coupled together via one or more network(s) **134**, e.g., the Internet and/or an enterprise intranet.

[0025] In the example of FIG. **1**A, NMS **130** is a cloud-based computing platform that manages wireless networks **106**A-**106**N at one or more of sites **102**A-**102**N. As further described herein, NMS **130** provides an integrated suite of management tools and implements various techniques of this disclosure. In general, NMS **130** may provide a cloud-based platform for wireless network data acquisition, monitoring, activity logging, reporting, predictive analytics, network anomaly identification, and alert generation. In some examples, NMS **130** outputs notifications, such as alerts, alarms, graphical indicators on dashboards, log messages, text/SMS messages, email messages, and the like, and/or recommendations regarding wireless network issues to a site or network administrator ("admin") interacting with and/or operating admin device **111**. Additionally, in some examples, NMS **130** operates in response to configuration input received from the administrator interacting with and/or operating admin device **111**.

[0026] The administrator and admin device **111** may comprise IT personnel and an administrator computing device associated with one or more of sites **102**. Admin device **111** may be implemented as any suitable device for presenting output and/or accepting user input. For instance, admin device **111** may include a display. Admin device **111** may be a computing system, such as a mobile or non-mobile computing device operated by a user and/or by the administrator. Admin device **111** may, for example, represent a workstation, a laptop or notebook computer, a desktop computer, a tablet computer, or any other computing device that may be operated by a user and/or present a user interface in accordance with one or more aspects of the present disclosure. Admin device **111** may be physically separate from and/or in a different location than NMS **130** such that admin device **111** may communicate with NMS **130** via network **134** or other means of communication.

[0027] In some examples, one or more of the NAS devices, e.g., APs **142**, switches **146**, or routers, may connect to edge devices **150**A-**150**N via physical cables, e.g., Ethernet cables. Edge devices **150** comprise cloud-managed, wireless local area network (LAN) controllers. Each of edge devices **150** may comprise an on-premises device at a site **102** that is in communication with NMS **130** to extend certain microservices from NMS **130** to the on-premises NAS devices while using NMS **130** and its distributed software architecture for scalable and resilient operations, management, troubleshooting, and analytics.

[0028] Each one of the network devices of network system **100**, e.g., servers **110**, **116**, **122** and/or **128**, APs **142**, UEs **148**, switches **146**, and any other servers or devices attached to or forming part of network system **100**, may include a system log or an error log module wherein each one of these network devices records the status of the network device including normal operational status and error conditions. Throughout this disclosure, one or more of the network devices of network system **100**, e.g., servers **110**, **116**, **122** and/or **128**, APs **142**, UEs **148**, and switches **146**, may be considered "third-party" network devices when owned by and/or associated with a different entity than NMS **130** such that NMS **130** does not receive, collect, or otherwise have access to the recorded status and other data of the third-party network devices. In some examples, edge devices **150** may provide a proxy through which the recorded status and other data of the third-party network devices may be reported to NMS **130**.

[0029] In some examples, NMS **130** monitors network data **137**, e.g., one or more service level expectation (SLE) metrics, received from wireless networks **106**A-**106**N at each site **102**A-**102**N, respectively, and manages network resources, such as APs **142** at each site, to deliver a high-quality wireless experience to end users, IoT devices and clients at the site. For example, NMS **130** may include a virtual network assistant (VNA) **133** that implements an event processing platform for providing real-time insights and simplified troubleshooting for IT operations, and that automatically takes corrective action or provides recommendations to proactively address wireless network issues. VNA **133** may, for example, include an event processing platform configured to process hundreds or thousands of concurrent streams of network data **137** from sensors and/or agents associated with APs **142** and/or nodes within network **134**. For example, VNA **133** of NMS **130** may include an underlying analytics and network error identification engine and alerting system in accordance with various examples described herein. The underlying analytics engine of VNA **133** may apply historical data and models to the inbound event streams to compute assertions, such as identified anomalies or predicted occurrences of events constituting network error conditions. Further, VNA **133** may provide real-time alerting and reporting to notify a site or network administrator via admin device **111** of any predicted events, anomalies, trends, and may perform root cause analysis and automated or assisted error remediation. In some examples, VNA **133** of NMS **130** may apply machine learning techniques to identify the root cause of error conditions detected or predicted from the streams of network data **137**. If the root cause may be automatically resolved, VNA **133** may invoke one or more corrective actions to correct the root cause of the error condition, thus automatically improving the underlying SLE metrics and also automatically improving the user experience.

[0030] Further example details of operations implemented by the VNA **133** of NMS **130** are described in U.S. Pat. No. 9,832,082, issued Nov. 28, 2017, and entitled "Monitoring Wireless Access Point Events," U.S. Publication No. US 2021/0306201, published Sep. 30, 2021, and entitled "Network System Fault Resolution Using a Machine Learning Model," U.S. Pat. No. 10,985,969, issued Apr. 20, 2021, and entitled "Systems and Methods for a Virtual Network

Assistant," U.S. Pat. No. 10,958,585, issued Mar. 23, 2021, and entitled "Methods and Apparatus for Facilitating Fault Detection and/or Predictive Fault Detection," U.S. Pat. No. 10,958,537, issued Mar. 23, 2021, and entitled "Method for Spatio-Temporal Modeling," and U.S. Pat. No. 10,862,742, issued Dec. 8, 2020, and entitled "Method for Conveying AP Error Codes Over BLE Advertisements," all of which are incorporated herein by reference in their entirety.

[0031] In operation, NMS **130** observes, collects and/or receives network data **137**, which may take the form of data extracted from messages, counters, and statistics, for example. In accordance with one specific implementation, a computing device is part of NMS **130**. In accordance with other implementations, NMS **130** may comprise one or more computing devices, dedicated servers, virtual machines, containers, services, or other forms of environments for performing the techniques described herein. Similarly, computational resources and components implementing VNA **133** may be part of the NMS **130**, may execute on other servers or execution environments, or may be distributed to nodes within network **134** (e.g., routers, switches, controllers, gateways, and the like).

[0032] NMS **130**, or more specifically, for example, device localization module **136**, may determine a location of devices at sites **102**. For example, device localization module **136** may implement a localization algorithm, such as multilateration techniques, to determine the location of a target device (e.g., AP, UE, etc.) of site **102**A based on distance measurements between the target device and one or more reference devices (e.g., APs with known locations) of site **102**A. For instance, pairs of APs of APs **142**A at site **102**A, such as AP **142**A-**1** and AP **142**A-N may exchange one or more signals to determine a distance between AP **142**A-**1** and AP **142**A-N according to a fine timing measurement (FTM) protocol. FTM protocols may be implemented to determine distance measurements based on round trip time (RTT) measurements of wireless signals (e.g., Wi-Fi signals) exchanged between AP **142**A-**1** and AP **142**A-N in accordance with, for example, an FTM protocol as described in IEEE 802.11-2016. In this example, the location of AP **142**A-**1** at site **102**A is known (and may represent a reference device) and the location of AP **142**A-N at site **102**A is unknown (and may represent a target device). AP **142**A-**1** and/or AP **142**A-N may determine the distance measurement between AP **142**A-**1** and AP **142**A-N based on a two-way time-of-flight (ToF) estimation of the one or more wireless signals exchanged between AP **142**A-**1** and AP **142**A-N, otherwise referred to as round trip time (RTT). NMS **130** may obtain the distance measurement between AP **142**A-**1** and AP **142**A-N and, based on the distance measurement between AP **142**A-**1** and AP **142**A-N, NMS **130** may determine the location of the target device, AP **142**A-N, relative to the reference device, AP **142**A-**1**. NMS **130** may obtain the distance measurements between other APs of APs **142**A at site **102**A. NMS **130** may also determine an orientation of APs **142** of site **102**A (e.g., a rotational position of the APs) based on, for example, reference APs with known positions. The orientation of APs **142** may indicate a rotational direction of the target device, AP **142-**N relative to the reference device, AP **142**A-**1**. Additional examples of determining the location of devices and placing devices on a site map are described in U.S. application Ser. No. 17/811,784, entitled "Determining Locations of Deployed Access Points," filed Jul. 11, 2022, and additional examples of determining the orientation of devices are described in U.S. Pat. No. 17,651,526, entitled "Determining Orientation of Deployed Access Points," filed Feb. 17, 2022, the entire contents of each of which is incorporated by reference herein. While the example described above is described with respect to APs **142** determining the distance measurements between APs **142** of sites **102**, NMS **130** may, in some examples, determine a distance measurement between the APs. For example, NMS **130** may obtain FTM data from APs **142** and determine the distance measurements between APs **142** based on the FTM data.

[0033] Based on the determined location and orientation of APs **142**A of site **102**A, NMS **130** may generate a site map that places APs **142**A on a map of site **102**A (e.g., place computer generated icons representing APs **142** on a site map). NMS **130** may maintain and manage a site map and provide the site map to an administrator of a network to enable the administrator to understand

and/or augment the deployment of devices at a site, such as for indoor wayfinding and asset positioning, and/or other applications. The site map may include suggestions for site managers on the placement of new devices and/or rearrangement of devices already installed at a site to improve location solutions with more accurate device positioning that may result in quicker resolution of coverage gaps or channel interference. Continuing the example described above, NMS **130** may generate a map that outlines the dimensions of site **102**A based on an image, blueprint, description, etc. of site **102**A provided by an administrator of site **102**A. NMS **130** may place a reference device (e.g., AP **142**A-**1** with a known location) on the map and place a target device (e.g., AP **142**A-N) on the map based on a location of the target device determined from the distance measurements between AP **142**A-**1** and AP **142**A-N.

[0034] In some instances, the use of multilateration techniques to determine the location of devices in a wireless network may result in ambiguous results (e.g., due to the degree of uncertainty and/or error of distance measurements based on fine timing measurements), such as when there are two or more possible locations for a device that are equidistant or near equidistant from at least one reference device. For instance, distance measurements for a target device that are determined from multilateration techniques may equally apply to two different positions of the target device. Ambiguous results may occur in instances where a device is in a more isolated and/or fringe sections of the site which may typically have a lower density of reference devices. With fewer reference devices, and thus less data to use in determining the location of devices, the location determination may be inaccurate, which may further result in the incorrect placement of devices on a site map.

[0035] In accordance with one or more techniques of this disclosure, NMS **130** is configured to determine the location of devices within sites **102** based on directional information of signals. For example, device localization module **136** of NMS **130** may obtain, in addition to the distance measurements, directional information of signals communicated between an antenna of at least one reference device and an antenna of the target device (e.g., directional information indicating a cardinal direction in degrees or radians relative to a reference device). The directional information may be included, for example, in wireless signals of communication protocols of a personal area network (e.g., BLUETOOTH low energy (BLE) signals or other 2.4 GHz signals). Based on the directional information of signals communicated between APs **142**, device localization module **136** of NMS **130** may determine whether there are any localization errors of APs **142**, such as when an AP is determined to be in a two or more possible positions. NMS **130** may, for example, determine whether directional information of a given AP (e.g., AP **142**A-**1**), determined from signals communicated between AP **142**A-**1** to a target AP (e.g., AP **142**A-N), is inconsistent with a an expected direction to AP **142**A-N (e.g., obtained from the determination of orientation of APs described above) and may generate a flag or other value that indicates a discrepancy in direction to the target device. For example, NMS **130** may obtain directional information from AP **142**A-**1** that specifies a first direction of a BLE signal communicated between AP **142**A-**1** and AP **142**A-N, and compare the first direction to a second direction indicative of an expected direction to AP **142**A-N. NMS **130** may determine that the first direction is inconsistent with the second direction and may generate a flag that indicates a discrepancy in directional information of AP **142**A-N relative to AP **142**A-**1**. NMS **130** may identify discrepancies of directional information of other APs **142** and generate a flag or other value for each instance a discrepancy in directional information is identified. NMS **130** may compare the number of flags to a threshold, and if the threshold is satisfied, NMS **130** may determine that there may be an error in the determined locations of APs **142**, such as an AP having two or more possible positions.

[0036] Alternatively, or additionally, NMS **130** may identify whether a distribution of possible positions of the target device form a multimodal distribution. For example, NMS **130** may generate a density plot based on the distance measurements (e.g., using a probability density function) between APs **142** and identify, for example, local maxima in the density plot that may be indicative of a possible position of the target device. If the distribution of distance measurements between APs **142** is multimodal (e.g., more than one local maxima in the density plot), NMS **130** may determine that there may be an error in the determined locations of APs **142**, such as an AP having two or more possible positions.

[0037] In response to determining a target AP having two or more possible positions, NMS **130** may resolve the ambiguity in the plurality of possible positions of the target device based on the directional information of signals. For example, NMS **130** may determine, from the directional information of a BLE signal communicated between the antenna of reference device AP **142**A-**1** and the antenna of target device AP **142**A-N, a candidate position of target device **142**A-N from among the two or more possible positions of target device **142**A-N. In some examples, NMS **130** may determine the candidate position based on directional information indicative of a direction in which one or more reference APs receive a loudest directional beam from the target AP and/or a direction in which the target AP receives a loudest directional beam from the one or more reference APs, as further described in FIG. **6**.

[0038] In some examples, NMS **130** may alternatively, or additionally, determine a candidate position of the target device based on information obtained from neighboring devices near the target device, as further described in FIG. **6**. For example, information from a neighboring device near (e.g., within range of a Wi-Fi signal) the target device may indicate the neighboring device detected a wireless signal from the target device and thus the target device is likely in a possible position near the neighboring device. Alternatively, NMS **130** may eliminate possible positions of the target device that the neighboring devices did not detect a wireless signal from the target device. In some examples, NMS **130** may confirm the determination of the candidate position based on directional information with the determination of the candidate position based the information indicating whether the neighboring device detected a wireless signal from the target device.

[0039] In some examples in which there are a limited number of reference devices (and thus a limited number of distance measurements), NMS **130** may add an error bias to possible positions of a target device based on a signal specifying the directional information deviating from an expected direction of the signal, as further described in FIG. **7**. As one example, AP **142**A-**1** may expect to receive a BLE signal from AP **142**A-N in a first direction (e.g., south-west direction) based on distance measurements between AP **142**A-N and AP **142**A-**1**. NMS **130** may, in this example, obtain directional information of a BLE signal received by AP **142**A-**1** from AP **142**A-N that specifies a second direction (e.g., south-east direction) that is inconsistent with the first direction, and in response, NMS **130** may add an error bias to possible positions corresponding to the first direction to indicate that possible positions of AP **142**A-N in the first direction is an unlikely position of AP **142**A-N. In this way, by adding an error bias to possible positions corresponding to directions of signals that deviate from expected directions of the signals, NMS **130** may collapse the multimodal distribution of possible positions of a target device to a single, likely candidate position.

[0040] In some examples, NMS **130** may alternatively, or additionally, eliminate possible positions of a target device where only a single reference device is able to perform distance measurements, as further described in FIG. **8**. The target device may be referred to herein as an “isolated target device.” In these examples, the target device is in range of a Wi-Fi signal (e.g., 5 GHz signal) from only a single reference device, but may be in range of a BLE signal (e.g., 2.4 GHz signal) from one or more other devices that are unable to detect a Wi-Fi signal from the target device. Due to the lack of reference devices, NMS **130** may determine the position of the target device with a greater degree of uncertainty, such as within a large window of possible positions (i.e., two or more positions). NMS **130** may eliminate possible positions of the target device, such as determining a probability window (e.g., a tight area representing possible locations of the target device) based on directional information of BLE signals communicated between the one or more other devices that are unable to detect a Wi-Fi signal from the target device.

[0041] The techniques of this disclosure provide one or more technical advantages and practical applications. For example, by applying directional information to a localization algorithm, the techniques described herein may disambiguate possible positions of a target device (e.g., equidistant points representing possible positions of a target device or possible positions with a greater degree of uncertainty), therefore providing a more accurate estimation of a location of the target device. Moreover, by integrating directional information to the localization algorithm, the techniques described herein may provide a more accurate estimation of a location of the target device with fewer measurements, such as when fine timing measurement data is sparse due to fewer reference devices and/or degraded signals resulting from walls or other environmental interference. For example, the directional information adds a degree of validity to fewer measurements, thus allowing for more accurate localizations with less known positions.

[0042] Although the techniques of the present disclosure are described in this example as performed by NMS **130**, techniques described herein may be performed by any other computing device(s), system(s), and/or server(s), and that the disclosure is not limited in this respect. For example, one or more computing device(s) configured to execute the functionality of the techniques of this disclosure may reside in a dedicated server or be included in any other server in addition to or other than NMS **130**, or may be distributed throughout network **100**, and may or may not form a part of NMS **130**.

[0043] FIG. **1**B is a block diagram illustrating further example details of the network system of FIG. **1**A. In this example, FIG. **1**B illustrates NMS **130** configured to operate according to an artificial intelligence/machine-learning-based computing platform providing comprehensive automation, insight, and assurance (WiFi Assurance, Wired Assurance and WAN assurance) spanning from “client,” e.g., user devices **148** connected to wireless network **106** and wired LAN **175** (far left of FIG. **1**B), to “cloud,” e.g., cloud-based application services **181** that may be hosted by computing resources within data centers **179** (far right of FIG. **1**B).

[0044] As described herein, NMS **130** provides an integrated suite of management tools and implements various techniques of this disclosure. In general, NMS **130** may provide a cloud-based platform for wireless network data acquisition, monitoring, activity logging, reporting, predictive analytics, network anomaly identification, and alert generation. For example, network management system **130** may be configured to proactively monitor and adaptively configure network **100** so as to provide self-driving capabilities. Moreover, VNA **133** includes a natural language processing engine to provide AI-driven support and troubleshooting, anomaly detection, AI-driven location services, and AI-driven radio frequency (RF) optimization with reinforcement learning.

[0045] As illustrated in the example of FIG. **1**B, AI-driven NMS **130** also provides configuration management, monitoring and automated oversight of software defined wide-area network (SD-WAN) **177**, which operates as an intermediate network communicatively coupling wireless networks **106** and wired LANs **175** to data centers **179** and application services **181**. In general, SD-WAN **177** provides seamless, secure, traffic-engineered connectivity between “spoke” routers **187**A of wired networks **175** hosting wireless networks **106**, such as branch or campus networks, to “hub” routers **187**B further up the cloud stack toward cloud-based application services **181**. SD-WAN **177** often operates and manages an overlay network on an underlying physical Wide-Area Network (WAN), which provides connectivity to geographically separate customer networks. In other words, SD-WAN **177** extends Software-Defined Networking (SDN) capabilities to a WAN and allows network(s) to decouple underlying physical network infrastructure from virtualized network infrastructure and applications such that the networks may be configured and managed in a flexible and scalable manner.

[0046] In some examples, underlying routers of SD-WAN **177** may implement a stateful, session-based routing scheme in which the routers **187**A, **187**B dynamically modify contents of original packet headers sourced by client devices **148** to steer traffic along selected paths, e.g., path **189**, toward application services **181** without requiring use of tunnels and/or additional labels. In this way, routers **187**A, **187**B may be more efficient and scalable for large networks since the use of tunnel-less, session-based routing may enable routers **187**A, **187**B to achieve considerable network resources by obviating the need to perform encapsulation and decapsulation at tunnel endpoints. Moreover, in some examples, each router **187**A, **187**B may independently perform path selection and traffic engineering to control packet flows associated with each session without requiring use of a centralized SDN controller for path selection and label distribution. In some examples, routers **187**A, **187**B implement session-based routing as Secure Vector Routing (SVR), provided by Juniper Networks, Inc.

[0047] Additional information with respect to session-based routing and SVR is described in U.S. Pat. No. 9,729,439, entitled “COMPUTER NETWORK PACKET FLOW CONTROLLER,” and issued on Aug. 8, 2017; U.S. Pat. No. 9,729,682, entitled “NETWORK DEVICE AND METHOD FOR PROCESSING A SESSION USING A PACKET SIGNATURE,” and issued on Aug. 8, 2017; U.S. Pat. No. 9,762,485, entitled “NETWORK PACKET FLOW CONTROLLER WITH EXTENDED SESSION MANAGEMENT,” and issued on Sep. 12, 2017; U.S. Pat. No. 9,871,748, entitled “ROUTER WITH OPTIMIZED STATISTICAL FUNCTIONALITY,” and issued on Jan. 16, 2018; U.S. Pat. No. 9,985,883, entitled “NAME-BASED ROUTING SYSTEM AND METHOD,” and issued on May 29, 2018; U.S. Pat. No. 10,200,264, entitled “LINK STATUS MONITORING BASED ON PACKET LOSS DETECTION,” and issued on Feb. 5, 2019; U.S. Pat. No. 10,277,506, entitled “STATEFUL LOAD BALANCING IN A STATELESS NETWORK,” and issued on Apr. 30, 2019; U.S. Pat. No. 10,432,522, entitled “NETWORK PACKET FLOW CONTROLLER WITH EXTENDED SESSION MANAGEMENT,” and issued on Oct. 1, 2019; and U.S. Pat. No. 11,075,824, entitled “IN-LINE PERFORMANCE MONITORING,” and issued on Jul. 27, 2021, the entire content of each of which is incorporated herein by reference in its entirety.

[0048] In some examples, AI-driven NMS **130** may enable intent-based configuration and management of network system **100**, including enabling construction, presentation, and execution of intent-driven workflows for configuring and managing devices associated with wireless networks **106**, wired LAN networks **175**, and/or SD-WAN **177**. For example, declarative requirements express a desired configuration of network components without specifying an exact native device configuration and control flow. By utilizing declarative requirements, what should be accomplished may be specified rather than how it should be accomplished. Declarative requirements may be contrasted with imperative instructions that describe the exact device configuration syntax and control flow to achieve the configuration. By utilizing declarative requirements rather than imperative instructions, a user and/or user system is relieved of the burden of determining the exact device configurations required to achieve a desired result of the user/system. For example, it is often difficult and burdensome to specify and manage exact imperative instructions to configure each device of a network when various different types of devices from different vendors are utilized. The types and kinds of devices of the network may dynamically change as new devices are added and device failures occur. Managing various different types of devices from different vendors with different configuration protocols, syntax, and software versions to configure a cohesive network of devices is often difficult to achieve. Thus, by only requiring a user/system to specify declarative requirements that specify a desired result applicable across various different types of devices, management and configuration of the network devices becomes more efficient. Further example details and techniques of an intent-based network management system are described in U.S. Pat. No. 10,756,983, entitled “Intent-based Analytics,” and U.S. Pat. No. 10,992,543, entitled “Automatically generating an intent-based network model of an existing computer network,” each of which is hereby incorporated by reference.

[0049] In accordance with the techniques described in this disclosure, NMS **130** may obtain distance measurement between at least two devices. NMS **130** may obtain distance measurements between, for example, a target device positioned at an unknown location and at least one reference device positioned at a known location. The target device may include a client device **148** or a device in wireless network **106**, such as an access point (e.g., AP **142** of FIG. **1**A) or other device configured to exchange wireless signals used to determine the distance between devices. The at least one reference device may include a device in wireless network **106**. Although described with respect to devices in wireless network **106**, the target device and/or reference device may include devices configured to exchange wireless signals in other networks.

[0050] NMS **130** may determine the location of the target device based on distance measurements between the target device and the at one reference device. For example, NMS **130** may obtain the distance measurements from the target device, the reference device, and/or other devices connected to the target device or the reference device, such as from network devices in wired network **175**, SD-WAN **177**, and/or from cloud-based application services **181** that may be hosted by computing resources within data centers **179** (far right of FIG. **1**B) that are communicatively coupled to the target device or the reference device. Based on the obtained distance measurements, NMS **130** may apply a localization algorithm, such as multilateration techniques, to determine possible positions of the target device.

[0051] NMS **130** may eliminate possible positions based on directional information specifying, for example, a direction of a signal (e.g., BLE signal) communicated between an antenna of the target device and an antenna of the reference device. For example, NMS **130** may obtain directional information of signals communicated in accordance with personal area network communication protocols implemented in wireless network **106**, such as Bluetooth/Bluetooth Low Energy (BLE) or other communication protocols that may include directional information of communicated signals. In some examples, NMS **130** may obtain the directional information from the target device, the reference device, and/or other devices connected to the target device or the reference device, such as from network devices in wired network **175**, SD-WAN **177**, and/or from cloud-based application services **181** that may be hosted by computing resources within data centers **179** (far right of FIG. **1**B) that are communicatively coupled to the target device or the reference device. NMS **130** may determine a candidate position of the target network device based on the directional information. For example, NMS **130** may eliminate possible positions of the target device based on directional information that specifies a direction of the signal communicated between the target device and the reference device is inconsistent with an expected direction of the signal.

[0052] FIG. **2** is a block diagram of an example access point (AP) device **200**, in accordance with one or more techniques of this disclosure. Example access point **200** and device localization module **236** shown in FIG. **2** may be used to implement any of APs **142** of FIG. **1**A and at least part of the functionality of device localization module **136**, respectively, as shown and described herein with respect to FIG. **1**A.

[0053] In the example of FIG. **2**, access point **200** includes a wired interface **230**, wireless interfaces **220**A-**220**B, one or more processor(s) **206**, memory **212**, and input/output **210**, coupled together via a bus **214** over which the various elements may exchange data and information. Wired interface **230** represents a physical network interface and includes a receiver **232** and a transmitter **234** for sending and receiving network communications, e.g., packets. Wired interface **230** couples, either directly or indirectly, access point **200** to a wired network device, such as one of switches **146** of FIG. **1**A, within the wired network via a cable, such as an Ethernet cable.

[0054] First and second wireless interfaces **220**A and **220**B represent wireless network interfaces and include receivers **222**A and **222**B, respectively, each including a receive antenna via which access point **200** may receive wireless signals from wireless communications devices, such as UEs **148** or other APs **142** of FIG. **1**A. First and second wireless interfaces **220**A and **220**B further include transmitters **224**A and **224**B, respectively, each including transmit antennas via which access point **200** may transmit wireless signals to wireless communications devices, such as UEs **148** or other APs **142** of FIG. **1**A. In some examples, first wireless interface **220**A may implement a first communication protocol, such as WI-FI 802.11 (e.g., 2.4 GHz and/or 5 GHZ), and second wireless interface **220**B may implement a second communication protocol, such as BLUETOOTH and/or a BLUETOOTH Low Energy (BLE).

[0055] Processor(s) **206** are programmable hardware-based processors configured to execute software instructions, such as those used to define a software or computer program, stored to a computer-readable storage medium (such as memory **212**), such as non-transitory computer-readable mediums including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processors **206** to perform the techniques described herein.

[0056] Memory **212** includes one or more devices configured to store programming modules and/or data associated with operation of access point **200**. For example, memory **212** may include a computer-readable storage medium, such as non-transitory computer-readable mediums including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processor(s) **206** to perform the techniques described herein.

[0057] In this example, memory **212** stores executable software including an application programming interface (API) **240**, a communications manager **242**, configuration settings **250**, a device status log **252**, data storage **254**, log controller **255**, and device localization module **236**. Device status log **252** includes a list of events specific to access point **200**. The events may include a log of both normal events and error events such as, for example, memory status, reboot or restart events, crash events, cloud disconnect with self-recovery events, low link speed or link speed flapping events, Ethernet port status, Ethernet interface packet errors, upgrade failure events, firmware upgrade events, configuration changes, etc., as well as a time and date stamp for each event. Log controller **255** determines a logging level for the device based on instructions from NMS **130**. Data **254** may store any data used and/or generated by access point **200**, including data collected from UEs **148**, such as data used to calculate one or more SLE metrics, that is transmitted by access point **200** for cloud-based management of wireless networks **106**A by NMS **130**. Device localization module **236** may include computer readable instructions for determining distance measurements, as well as directional information, between access point **200** and another device in communication with access point **200** (a reference or target device) to determine the location of access point **200** or the other device in communication with access point **200**, as further described below.

[0058] Input/output (I/O) **210** represents physical hardware components that enable interaction with a user, such as buttons, a display, and the like. Although not shown, memory **212** typically stores executable software for controlling a user interface with respect to input received via I/O **210**. Communications manager **242** includes program code that, when executed by processor(s) **206**, allow access point **200** to communicate with UEs **148** and/or network(s) **134** via any of interface(s) **230** and/or **220**A-**220**B. Configuration settings **250** include any device settings for access point **200** such as radio settings for each of wireless interface(s) **220**A-**220**B. These settings may be configured manually or may be remotely monitored and managed by NMS **130** to optimize wireless network performance on a periodic (e.g., hourly or daily) basis.

[0059] As described herein, AP device **200** may measure and report network data from status log **252** to NMS **130**. The network data may comprise event data, telemetry data, and/or other SLE-related data. The network data may include various parameters indicative of the performance and/or status of the wireless network. The parameters may be measured and/or determined by one or more of the UE devices and/or by one or more of the APs in a wireless network. NMS **130** may determine one or more SLE metrics based on the SLE-related data received from the APs in the wireless network and store the SLE metrics as network data **137** (FIG. **1**A).

[0060] In accordance with the techniques described herein, access point **200** may, in some examples, include device localization module **236** that is configured to determine the location of access point **200** or another device in communication with access point **200** based on directional information of signals communicated between the access point **200** and the other device in communication with access point **200**. In instances where access point **200** operates as a reference device to a target device, device localization module **236** may instruct wireless interfaces **220**A, for example, to send a wireless signal (e.g., a Wi-Fi signal) to the target device and determine a distance between access point **200** and the target device. Device localization module **236** may determine the distance between access point **200** and the target device based on distance measurements determined in accordance with FTM protocols described in IEEE 802.11-2016. For example, device localization module **236** may perform a two-way ToF estimation of the wireless signals communicated between access point **200** and the target device. Device localization module **236** may implement a localization algorithm, such as multilateration techniques, using the distance measurements to determine possible positions of the target device. For example, device localization module **236** may plot possible positions of the target device based on a probability distribution function, and determine whether the distribution forms a multimodal distribution (where there is more than one local maxima in the distribution), which may indicate a plurality of possible positions of the target device relative to access point **200**.

[0061] In response to determining a plurality of possible positions of the target device, device localization module **236** may obtain directional information specifying a direction of wireless signals communicated between access point **200** and the target device. For example, device localization module **236** may determine a direction a wireless signal is communicated between access point **200** and the target device. Device localization module **236** may, for example, determine the direction of the wireless signal based on a direction in which wireless interface **220**B, or more specifically a receive antenna of receiver **222**B, receives the strongest directional beam signals originating from the target device.

[0062] In operation, device localization module **236** may, based on the directional information, determine whether there are any localization errors in an expected direction of a target device relative to AP **200**. Device localization module **236** may determine discrepancies between directional information specifying a direction of wireless signals communicated between access point **200** and the target device and an expected direction of the target device location (e.g., determined based on distance measurements between the target device and access point **200**). For example, device localization module **236** may determine whether directional information of a target device relative to AP **200** is inconsistent with a relative direction the target device is located to AP **200**. Device localization module **236** may generate a flag or other value that indicates a determined discrepancy in direction of the target device relative to AP **200**. For example, device localization module **236** may obtain directional information specifying a first direction of a BLE signal communicated between wireless interface **220**B and a wireless interface of a target device, and compare the first direction to a second direction indicative of a relative direction the target device is located with respect to AP **200**. Device localization module **236** may determine the first direction is inconsistent with the second direction and may generate a flag that indicates a discrepancy in the direction of the target device relative to AP **200**.

[0063] In some instances, device localization module **236** may alternatively or additionally determine a localization error by identifying whether a distribution of possible positions of the target device form a multimodal distribution. For example, device localization module **236** may generate a density plot based on the distance measurements (e.g., using a probability density function) between AP **200** and a target device. Device localization module **236** may identify, for example, local maxima in the density plot that may be indicative of a possible position of the target device. If device localization module **236** identifies more than one local maxima in the density plot, device localization module **236** may determine the distribution of distance measurements between AP **200** and the target device is multimodal. Device localization module **236**, responsive to determining the distribution is multimodal, may determine that there may be an error in the determined location of the target device, such as the target device having two or more possible positions.

[0064] In response to device localization module **236** determining an error in the expected location of the target device, device localization module **236** may resolve any ambiguity in the plurality of possible positions of the target device based on the directional information. For example, device localization module **236** may determine, from the directional information of a BLE signal communicated between an antenna of wireless interface **220**B and an antenna of a target device, a candidate position of the target device from among two or more possible positions of the target device. For example, device localization module **236** may determine the candidate position of the target device based on an error bias applied to possible positions in the multimodal distribution specifying likelihoods of possible positions of the target device. In these examples, device localization module **236** may add an error bias to a possible position of the target device in the multimodal distribution in which a direction specified in directional information of signals communicated between AP **200** and the target device deviate from a direction of a possible position of the target device determined from distance measurements to reduce the multimodal distribution to a single candidate position corresponding to a direction specified in the directional information. Device localization module **236** may send the candidate position to a network management system (e.g., NMS **130** of FIG. **1**A) to place the target device relative to access point **200** on a site map of a site. In instances where access point **200** is a target device, access point **200** may operate substantially similar to the access point operating as a reference device, as described above.

[0065] In some instances, access point **200** may determine a target device may be an isolated target device (e.g., a device having two or fewer reference devices are available to determine the location and/or orientation of the target device based on distance measurements). For example, device localization module **236** may determine that there are less than three distance measurements for the target device and may flag the target device as an isolated target device that has a limited amount of data to triangulate the location of the target device. Device localization module **236** may determine a candidate position of the isolated target based on the distance measurements, for example, by adding error biases to possible positions of the target device in the multimodal distribution in which the positional direction of the target device deviates from the direction of the BLE signal.

[0066] In some examples in which there is only one reference device to perform distance measurements, device localization module **236** may determine a probability window (e.g., a tight area representing possible locations of access point **200**) of a candidate position. For example, device localization module **236** may determine a large probability band of possible positions of the target device based on distance measurements between the target device and the single reference device. Device localization module **236** may refine the probability band of possible positions to a probability window of a most likely position of the target device. For example, device localization module **236** may determine the probability window of a candidate position based on directional information of BLE signals communicated between one or more other devices and the target device, where the target device is not in range of the Wi-Fi signals of the one or more other devices.

[0067] FIG. **3** are block diagrams of an example network management system (NMS) **300**, in accordance with one or more techniques of the disclosure. NMS **300** may be used to implement, for example, NMS **130** in FIGS. **1**A-**1**B. In such examples, NMS **300** is responsible for monitoring and management of one or more wireless networks **106**A-**106**N at sites **102**A-**102**N, respectively.

[0068] NMS **300** includes a communications interface **330**, one or more processor(s) **306**, a user interface **310**, a memory **312**, and a database **318**. The various elements are coupled together via a bus **314** over which the various elements may exchange data and information. In some examples, NMS **300** receives data from one or more of client devices **148**, APs **142**, switches **146** and other network nodes within network **134**, e.g., routers **187** of FIG. **1**B, which may be used to calculate one or more SLE metrics and/or update network data **316** in database **318**. NMS **300** analyzes this data for cloud-based management of wireless networks **106**A-**106**N. In some examples, NMS **300** may be part of another server shown in FIG. **1**A or a part of any other server.

[0069] Processor(s) **306** execute software instructions, such as those used to define a software or computer program, stored to a computer-readable storage medium (such as memory **312**), such as non-transitory computer-readable mediums including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processors **306** to perform the techniques described herein.

[0070] Communications interface **330** may include, for example, an Ethernet interface. Communications interface **330** couples NMS **300** to a network and/or the Internet, such as any of network(s) **134** as shown in FIG. **1**A, and/or any local area networks.

[0071] Communications interface **330** includes a receiver **332** and a transmitter **334** by which NMS **300** receives/transmits data and information to/from any of client devices **148**, APs **142**, switches **146**, servers **110**, **116**, **122**, **128** and/or any other network nodes, devices, or systems forming part of network system **100** such as shown in FIG. **1**A. In some scenarios described herein in which network system **100** includes “third-party” network devices that are owned and/or associated with different entities than NMS **300**, NMS **300** does not receive, collect, or otherwise have access to network data from the third-party network devices.

[0072] The data and information received by NMS **300** may include, for example, telemetry data, SLE-related data, or event data received from one or more of client device APs **148**, APs **142**, switches **146**, or other network nodes, e.g., routers **187** of FIG. **1**B, used by NMS **300** to remotely monitor the performance of wireless networks **106**A-**106**N and application sessions from client device to cloud-based application server. NMS **300** may further transmit data via communications interface **330** to any of network devices such as client devices **148**, APs **142**, switches **146**, other network nodes within network **134**, admin device **111** to remotely manage wireless networks **106**A-**106**N and portions of the wired network.

[0073] Memory **312** includes one or more devices configured to store programming modules and/or data associated with operation of NMS **300**. For example, memory **312** may include a computer-readable storage medium, such as a non-transitory computer-readable medium including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processor(s) **306** to perform the techniques described herein.

[0074] In this example, memory **312** includes an API **320**, an SLE module **322**, a virtual network assistant (VNA)/AI engine **350**, a radio resource management (RRM) engine **360**, and device localization module **356**. NMS **300** may also include any other programmed modules, software engines and/or interfaces configured for remote monitoring and management of wireless networks **106**A-**106**N and portions of the wired network, including remote monitoring and management of any of APs **142**/**200**, switches **146**, or other network devices, e.g., routers **187** of FIG. **1**B.

[0075] SLE module **322** enables set up and tracking of thresholds for SLE metrics for each network **106**A-**106**N. SLE module **322** further analyzes SLE-related data collected by APs, such as any of APs **142** from UEs in each wireless network **106**A-**106**N. For example, APs **142**A-**1** through **142**A-N collect SLE-related data from UEs **148**A-**1** through **148**A-N currently connected to wireless network **106**A. This data is transmitted to NMS **300**, which executes by SLE module **322** to determine one or more SLE metrics for each UE **148**A-**1** through **148**A-N currently connected to wireless network **106**A. This data, in addition to any network data collected by one or more APs **142**A-**1** through **142**A-N in wireless network **106**A, is transmitted to NMS **300** and stored as, for example, network data **316** in database **318**.

[0076] RRM engine **360** monitors one or more metrics for each site **102**A-**102**N in order to learn and optimize the RF environment at each site. For example, RRM engine **360** may monitor the coverage and capacity SLE metrics for a wireless network **106** at a site **102** in order to identify potential issues with SLE coverage and/or capacity in the wireless network **106** and to make adjustments to the radio settings of the access points at each site to address the identified issues. For example, RRM engine may determine channel and transmit power distribution across all APs **142** in each network **106**A-**106**N. For example, RRM engine **360** may monitor events, power, channel, bandwidth, and number of clients connected to each AP. RRM engine **360** may further automatically change or update configurations of one or more APs **142** at a site **102** with an aim to improve the coverage and capacity SLE metrics and thus to provide an improved wireless experience for the user.

[0077] VNA/AI engine **350** analyzes data received from network devices as well as its own data to identify when undesired to abnormal states are encountered at one of the network devices. For example, VNA/AI engine **350** may identify the root cause of any undesired or abnormal states, e.g., any poor SLE metric(s) indicative of connected issues at one or more network devices. In addition, VNA/AI engine **350** may automatically invoke one or more corrective actions intended to address the identified root cause(s) of one or more poor SLE metrics. Examples of corrective actions that may be automatically invoked by VNA/AI engine **350** may include, but are not limited to, invoking RRM **360** to reboot one or more APs, adjusting/modifying the transmit power of a specific radio in a specific AP, adding SSID configuration to a specific AP, changing channels on an AP or a set of APs, etc. The corrective actions may further include restarting a switch and/or a router, invoking downloading of new software to an AP, switch, or router, etc. These corrective actions are given for example purposes only, and the disclosure is not limited in this respect. If automatic corrective actions are not available or do not adequately resolve the root cause, VNA/AI engine **350** may proactively provide a notification including recommended corrective actions to be taken by IT personnel, e.g., a site or network administrator using admin device **111**, to address the network error.

[0078] Device localization module **356** may determine a position of a target network device. Device localization module **356** may include an example or alternative implementation of device localization module **236** of FIG. **2**. For example, device localization module **356** may determine distance measurements between a target device and at least one reference device according to an FTM protocol (e.g., by receiving RTT data from the at least one reference device and/or the target device). Device localization module **356** may also obtain directional information of signals communicated between the target device and the at least one reference device. Device localization module **356** may determine two or more possible positions of the target device based on the distance measurements and directional information (e.g., by determining an expected direction of the target device relative to the at least one reference device is inconsistent with the directional information). Device localization module **356** may determine a candidate position from the two or more possible positions based on the directional information.

[0079] In the example of FIG. **3**, device localization module **356** may include distance module **358**, orientation module **359**, directional validation module **362**, correction module **363**, and site mapping module **364**. Distance module **358** may obtain distance measurements between a target device positioned at an unknown location within a site and one or more reference devices positioned at known locations within the site. Distance module **358** may determine an approximate location of a target device based on distance measurements between the target device and one or more reference devices. Orientation module **359** may obtain received signal strength measurements of wireless signals originating at one or more antennas of a target device and received by one or more antennas of a reference device, or vice versa. Orientation module **359** may determine an orientation angle a target device is located relative to a reference device based on the received signal strength measurements, for example. Directional validation module **362** may obtain directional information of signals communicated between a target device and one or more reference devices. Directional validation module **362** may determine discrepancies between an orientation of a target device, as determined by orientation module **359**, for example, and the directional information. Correction module **363** may determine, based on the directional information, a candidate position to correct any discrepancies. Site map module **364** may generate a map including relative locations of the target device and the one or more reference devices based on the known locations of the one or more reference devices, as well as the candidate position of the target device.

[0080] Distance module **358** may determine a location of a target device at a site based on distance measurements between the target device and one or more reference devices. For example, distance module **358** may obtain distance measurements determined based on RTT measurements of wireless signals exchanged between the target device and one or more reference devices. Distance module **358** may implement a localization algorithm (e.g., multilateration techniques) to determine one or more possible positions of the target device based on the distance measurements specifying a distance the target device is located relative to one or more reference devices. In general, distance module **358** may determine possible positions of any device at a site based on distance measurements between the devices at the site.

[0081] Orientation module **359** may determine an orientation (e.g., rotational position of a device at a site relative to other devices) of a target device based on the distance measurements. For example, orientation module **359** may obtain distance measurements determined based on received signal strength measurements of wireless signals transmitted by one or more antennas of a reference device and received by one or more antennas of a target device, or vice versa. Orientation module **359** may determine the orientation of the target device based on an orientation angle, included in the distance measurements, specifying a rotational position a target device is located relative to a reference device. In some examples, orientation module **359** may determine the orientation of a target device based on orientation angles of reference devices with known positions at a site. Orientation module **359** may determine the orientation of a target device as an indication of a rotational direction a target device is located relative to one or more reference devices. Orientation module **359** may obtain the one or more possible positions of the target device determined by distance module **358**. Orientation module **359** may adjust the possible positions of the target device based on the determined orientation.

[0082] Directional validation module **362** may determine discrepancies between an expected location of a target device and directional information of wireless signals communicated between the target device and one or more reference devices. Directional validation module **362** obtain directional information of signals communicated between a target device and at least one reference device at a site. For example, directional validation module **362** may obtain directional information from a target device and/or reference devices that includes a direction the target device is located relative to the reference devices based on a BLE signal communicated between the target device and the reference devices. Directional validation module **362** may collect directional information between devices at a site in parallel, or at the same time as, distance module **358** and/or orientation module **359** collect distance measurements between devices at the site. Directional validation module **362** may check for discrepancies between expected directions the target device is located relative to reference devices and directional information of signals communicated between the target device and the reference devices. For example, directional validation module **362** may determine an expected direction a target device is located relative to a reference device based on possible positions of the target device determined by distance module **358** and/or orientation module **359**. Directional validation module **362** may flag a discrepancy in response to determining the expected direction of the target device relative to the reference device is inconsistent with the directional information between the target device and the reference device. For example, directional information module **362** may flag discrepancies, such as when an expected direction of a target device relative to a reference device is inconsistent by at least 45 degrees compared to directional information of signals communicated between the target device and the reference device. Directional validation module **362** may flag multiple discrepancies by determining multiple inconsistencies with expected directions of the target device and multiple devices is consistent with corresponding directional information. Directional validation module **362** may determine a localization error (e.g., the target device located at two or more possible positions) based on the number of flagged discrepancies for a target device satisfying a threshold. In response to determining a localization error, directional validation module **362** may relay an indication of the localization error (e.g., two or more possible positions of a target device) and the directional information to correction module **363**.

[0083] Correction module **363** may correct a localization error based on the directional information. Correction module **363** may determine a candidate position from two or more possible positions (e.g., as indicated in a localization error) of a target device based on the directional information. In some instances, correction module **363** may select a candidate position of the two or more possible positions based on a possible position that is consistent with the directional information. In some examples, correction module **363** may eliminate possible positions from the two or more possible positions based on a possible position being inconsistent with the directional information. If correction module **363** determines more than one candidate position is not inconsistent with the directional information, correction module **363** may re-determine whether the more than one candidate position results in a discrepancy when compared to directional information associated with the target device and one or more additional reference devices. For example, correction module **363** may obtain additional directional information of signals communicated between the target device and another reference device that may be on a different level at the site (e.g., above or below the candidate position).

[0084] Additionally, or alternatively, directional validation module **362** may generate a density plot of possible positions. In some instances, directional validation module **362** may generate the density plot of possible positions based on distance measurements obtained by distance module **358** and/or orientation module **359**. Directional validation module **362** may determine the density plot is multimodal. In other words, directional validation module **362** may determine the more than one local maxima in the density plot of possible positions. Directional validation module **362** may add error biases to the density plot of possible positions based on the directional information of signals communicated between the target device and at least one reference device. Directional validation module **362** may send the density plot of possible positions with the applied error biases to correction module **363**. Correction module **363** may determine a candidate position based on the density plot of possible positions with the error biases. For example, correction module **363** may determine a candidate position by eliminating possible positions on the density plot based on a degree of an error bias applied to the possible positions. Correction module **363** may send the candidate position to site mapping module **364**. Site mapping module **364** may place a user interface element (e.g., a computer-generated icon representing a device) indicating a location of the target device on a site map based on the candidate position.

[0085] In some examples, directional validation module **362** may flag a target device as an isolated device. Directional validation module **362** may determine a target device is an isolated device when the target device is associated with fewer than three reference devices. Directional validation module **362** may determine an isolated target device has an inherent localization error as a result of the scarcity of data available to determine the location of a target device. For example, directional validation module **362** may determine that there are less than three distance measurements for the target device and may flag the target device as an isolated target device that has a limited amount of data to triangulate the location of the target device. In this example, directional validation module **362** may obtain directional information between the target device and other devices that may be proximate to a possible position of the target device but is isolated from the target device in terms of being unable to communicate with the target device to determine distance measurements. Directional validation module **362** may provide the directional information to correction module **363**. Correction module **362** may eliminate possible positions of a target device and/or refine a location of the target device to a probability window of where the target device is likely located based on the directional information.

[0086] The techniques of this disclosure provide one or more technical advantages and practical applications. For example, NMS **300** utilizes a new dimension of data (e.g., directional information obtained based on directional signals sent and received by a target device and/or one or more reference devices) to validate and/or further refine placement of a target device on a site map. NMS **300** may obtain directional information to disambiguate possible positions of a target device that may be associated with two or more equidistant points relative to one or more reference devices on a site map. NMS **300** may disambiguate possible positions by eliminating at least one of these possible positions based on inconsistencies of expected directions the target device is located relative to reference devices and corresponding directional information. NMS **300** may bolster sparse FTM data in fringe sections of the map. NMS **300** may use the directional information to add a degree of validity to fewer amounts of distance measurements. In this way, NMS **300** may apply the directional information to allow for more accurate localizations of devices with less known positions (e.g., a fewer number of reference devices). In general, NMS **300** may rely on directional information of signals communicated between devices at a site as a reliable source of information, compared to locations of devices determined based on distance measurements.

[0087] Although the techniques of the present disclosure are described in this example as performed by NMS **130**, techniques described herein may be performed by any other computing device(s), system(s), and/or server(s), and that the disclosure is not limited in this respect. For example, one or more computing device(s) configured to execute the functionality of the techniques of this disclosure may reside in a dedicated server or be included in any other server in addition to or other than NMS **130**, or may be distributed throughout network **100**, and may or may not form a part of NMS **130**.

[0088] FIG. **4** shows an example user equipment (UE) device **400**, in accordance with one or more techniques of this disclosure. Example UE device **400** and device localization module **436** shown in FIG. **4** may be used to implement any of UEs **148** and device localization module **134**, respectively, as shown and described herein with respect to FIG. **1**A. UE device **400** may include any type of wireless client device, and the disclosure is not limited in this respect. For example, UE device **400** may include a mobile device such as a smart phone, tablet or laptop computer, a personal digital assistant (PDA), a wireless terminal, a smart watch, a smart ring, or any other type of mobile or wearable device. In some examples, UE **400** may also include a wired client-side device, e.g., an IoT device such as a printer, a security sensor or device, an environmental sensor, or any other device connected to the wired network and configured to communicate over one or more wireless networks.

[0089] UE device **400** includes a wired interface **430**, wireless interfaces **420**A-**420**C, one or more processor(s) **406**, memory **412**, and a user interface **410**. The various elements are coupled together via a bus **414** over which the various elements may exchange data and information. Wired interface **430** represents a physical network interface and includes a receiver **432** and a transmitter **434**. Wired interface **430** may be used, if desired, to couple, either directly or indirectly, UE **400** to a wired network device, such as one of switches **146** of FIG. **1**A, within the wired network via a cable, such as one of Ethernet cables **144** of FIG. **1**A.

[0090] First, second and third wireless interfaces **420**A, **420**B, and **420**C include receivers **422**A, **422**B, and **422**C, respectively, each including a receive antenna via which UE **400** may receive wireless signals from wireless communications devices, such as APs **142** of FIG. **1**A, AP **200** of FIG. **2**, other UEs **148**, or other devices configured for wireless communication. First, second, and third wireless interfaces **420**A, **420**B, and **420**C further include transmitters **424**A, **424**B, and **424**C, respectively, each including transmit antennas via which UE **400** may transmit wireless signals to wireless communications devices, such as APs **142** of FIG. **1**A, AP **200** of FIG. **2**, other UEs **148** and/or other devices configured for wireless communication. In some examples, first wireless interface **420**A may include a Wi-Fi 802.11 interface (e.g., 2.4 GHz and/or 5 GHZ) and second wireless interface **420**B may include a Bluetooth interface and/or a Bluetooth Low Energy interface. Third wireless interface **420**C may include, for example, a cellular interface through which UE device **400** may connect to a cellular network.

[0091] Processor(s) **406** execute software instructions, such as those used to define a software or computer program, stored to a computer-readable storage medium (such as memory **412**), such as non-transitory computer-readable mediums including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processors **406** to perform the techniques described herein.

[0092] Memory **412** includes one or more devices configured to store programming modules and/or data associated with operation of UE **400**. For example, memory **412** may include a computer-readable storage medium, such as non-transitory computer-readable mediums including a storage device (e.g., a disk drive, or an optical drive) or a memory (such as Flash memory or RAM) or any other type of volatile or non-volatile memory, that stores instructions to cause the one or more processor(s) **406** to perform the techniques described herein.

[0093] In this example, memory **412** includes an operating system **440**, applications **442**, a communications module **444**, configuration settings **450**, data storage **454**, and device localization module **436**. Communications module **444** includes program code that, when executed by processor(s) **406**, enables UE **400** to communicate using any of wired interface(s) **430**, wireless interfaces **420**A-**420**B and/or cellular interface **450**C. Configuration settings **450** include any device settings for UE **400** settings for each of wireless interface(s) **420**A-**420**B and/or cellular interface **420**C.

[0094] Data storage **454** may include, for example, a status/error log including a list of events specific to UE **400**. The events may include a log of both normal events and error events according to a logging level based on instructions from NMS **130**. Data storage **454** may store any data used and/or generated by UE **400**, such as data used to calculate one or more SLE metrics or identify relevant behavior data, that is collected by UE **400** and either transmitted directly to NMS **130** or transmitted to any of APs **142** in a wireless network **106** for further transmission to NMS **130**.

[0095] As described herein, UE **400** may measure and report network data from data storage **454** to NMS **130**. The network data may comprise event data, telemetry data, and/or other SLE-related data. The network data may include various parameters indicative of the performance and/or status of the wireless network. NMS **130** may determine one or more SLE metrics and store the SLE metrics as network data **137** (FIG. **1**A) based on the SLE-related data received from the UEs or client devices in the wireless network.

[0096] Optionally, UE device **400** may include an NMS agent **456**. NMS agent **456** is a software agent of NMS **130** that is installed on UE **400**. In some examples, NMS agent **456** can be implemented as a software application running on UE **400**. NMS agent **456** collects information including detailed client-device properties from UE **400**, including insight into UE **400** roaming behaviors. The information provides insight into client roaming algorithms, because roaming is a client device decision. In some examples, NMS agent **456** may display the client-device properties on UE **400**. NMS agent **456** sends the client device properties to NMS **130**, via an AP device to which UE **400** is connected. NMS agent **456** can be integrated into a custom application or as part of location application. NMS agent **456** may be configured to recognize device connection types (e.g., cellular or Wi-Fi), along with the corresponding signal strength. For example, NMS agent **456** recognizes access point connections and their corresponding signal strengths. NMS agent **456** can store information specifying the APs recognized by UE **400** as well as their corresponding signal strengths. NMS agent **456** or other element of UE **400** also collects information about which APs the UE **400** connected with, which also indicates which APs the UE **400** did not connect with. NMS agent **456** of UE **400** sends this information to NMS **130** via its connected AP. In this manner, UE **400** sends information about not only the AP that UE **400** connected with, but also information about other APs that UE **400** recognized and did not connect with, and their signal strengths. The AP in turn forwards this information to the NMS, including the information about other APs the UE **400** recognized besides itself. This additional level of granularity enables NMS **130**, and ultimately network administrators, to better determine the Wi-Fi experience directly from the client device's perspective.

[0097] In some examples, NMS agent **456** further enriches the client device data leveraged in service levels. For example, NMS agent **456** may go beyond basic fingerprinting to provide supplemental details into properties such as device type, manufacturer, and different versions of operating systems. In the detailed client properties, the NMS **130** can display the Radio Hardware and Firmware information of UE **400** received from NMS client agent **456**. The more details the NMS agent **456** can draw out, the better the VNA/AI engine gets at advanced device classification. The VNA/AI engine of the NMS **130** continually learns and becomes more accurate in its ability to distinguish between device-specific issues or broad device issues, such as specifically identifying that a particular OS version is affecting certain clients.

[0098] In some examples, NMS agent **456** may cause user interface **410** to display a prompt that prompts an end user of UE **400** to enable location permissions before NMS agent **456** is able to report the device's location, client information, and network connection data to the NMS. NMS agent **456** will then start reporting connection data to the NMS along with location data. In this manner, the end user of the client device can control whether the NMS agent **456** is enabled to report client device information to the NMS.

[0099] In some examples, UE device **400** includes device localization module **436**. UE device **400** may be configured to include device localization module **436** in examples where UE device **400** is a stationary UE device that an administrator would like to place on a map to suggest improvements to network coverage and/or to diagnose network issues. Device localization module **436** of UE device **400** may include an example or alternative implementation of device localization module **236** of FIG. **2** or device localization module **336** of FIG. **3**.

[0100] FIG. **5** is a block diagram illustrating an example network device **500**, in accordance with one or more techniques of this disclosure. In one or more examples, the network device **500** implements a device or a server attached to the network **134** of FIG. **1**A, e.g., switches **146**, AAA server **110**, DHCP server **116**, DNS server **122**, web servers **128**, etc., or another network device supporting one or more of wireless network **106**, wired LAN **175**, or SD-WAN **177**, or data center **179** of FIG. **1**B, e.g., routers **187**.

[0101] In this example, network device **500** includes a wired interface **502**, e.g., an Ethernet interface, a processor **506**, input/output **508**, e.g., display, buttons, keyboard, keypad, touch screen, mouse, etc., wireless interfaces **520**A and **520**B, e.g., personal area network interface or local area network interface, etc., and a memory **512** coupled together via a bus **514** over which the various elements may interchange data and information. Wired interface **502** couples the network device **500** to a network, such as an enterprise network. Though only one interface is shown by way of example, network nodes may, and usually do, have multiple communication interfaces and/or multiple communication interface ports. Wired interface **502** includes a receiver **520** and a transmitter **522**.

[0102] Memory **512** stores executable software applications **532**, operating system **540** and data/information **530**. Data **530** may include a system log and/or an error log that stores event data, including behavior data, for network device **500**. In examples where network device **500** comprises a “third-party” network device, the same entity does not own or have access to both the APs or wired client-side devices and network device **500**. As such, in the example where network device **500** is a third-party network device, NMS **130** does not receive, collect, or otherwise have access to the network data from network device **500**.

[0103] In examples where network device **500** comprises a server, network device **500** may receive data and information, e.g., including operation related information, e.g., registration request, AAA services, DHCP requests, Simple Notification Service (SNS) look-ups, and Web page requests via receiver **520**, and send data and information, e.g., including configuration information, authentication information, web page data, etc. via transmitter **522**.

[0104] In examples where network device **500** comprises a wired network device, network device **500** may be connected via wired interface **502** to one or more APs or other wired client-side devices, e.g., IoT devices. For example, network device **500** may include multiple wired interfaces **502** and/or wired interface **502** may include multiple physical ports to connect to multiple APs or the other wired-client-side devices within a site via respective Ethernet cables. In some examples, each of the APs or other wired client-side devices connected to network device **500** may access the wired network via wired interface **502** of network device **500**. In some examples, one or more of the APs or other wired client-side devices connected to network device **500** may each draw power from network device **500** via the respective Ethernet cable and a Power over Ethernet (POE) port of wired interface **502**.

[0105] In examples where network device **500** comprises a session-based router that employs a stateful, session-based routing scheme, network device **500** may be configured to independently perform path selection and traffic engineering. The use of session-based routing may enable network device **500** to eschew the use of a centralized controller, such as an SDN controller, to perform path selection and traffic engineering, and eschew the use of tunnels. In some examples, network device **500** may implement session-based routing as Secure Vector Routing (SVR), provided by Juniper Networks, Inc. In the case where network device **500** comprises a session-based router operating as a network gateway for a site of an enterprise network (e.g., router **187**A of FIG. **1**B), network device **500** may establish multiple peer paths (e.g., logical path **189** of FIG. **1**B) over an underlying physical WAN (e.g., SD-WAN **177** of FIG. **1**B) with one or more other session-based routers operating as network gateways for other sites of the enterprise network (e.g., router **187**B of FIG. **1**B). Network device **500**, operating as a session-based router, may collect data at a peer path level, and report the peer path data to NMS **130**.

[0106] In examples where network device **500** comprises a packet-based router, network device **500** may employ a packet- or flow-based routing scheme to forward packets according to defined network paths, e.g., established by a centralized controller that performs path selection and traffic engineering. In the case where network device **500** comprises a packet-based router operating as a network gateway for a site of an enterprise network (e.g., router **187**A of FIG. **1**B), network device **500** may establish multiple tunnels (e.g., logical path **189** of FIG. **1**B) over an underlying physical WAN (e.g., SD-WAN **177** of FIG. **1**B) with one or more other packet-based routers operating as network gateways for other sites of the enterprise network (e.g., router **187**B of FIG. **1**B). Network device **500**, operating as a packet-based router, may collect data at a tunnel level, and the tunnel data may be retrieved by NMS **130** via an API or an open configuration protocol or the tunnel data may be reported to NMS **130** by NMS agent **544** or other module running on network device **500**.

[0107] The data collected and reported by network device **500** may include periodically-reported data and event-driven data. Network device **500** is configured to collect logical path statistics via bidirectional forwarding detection (BFD) probing and data extracted from messages and/or counters at the logical path (e.g., peer path or tunnel) level. In some examples, network device **500** is configured to collect statistics and/or sample other data according to a first periodic interval, e.g., every 3 seconds, every 5 seconds, etc. Network device **500** may store the collected and sampled data as path data, e.g., in a buffer.

[0108] In some examples, network device **500** optionally includes an NMS agent **544**. NMS agent **544** may periodically create a package of the statistical data according to a second periodic interval, e.g., every 3 minutes. The collected and sampled data periodically-reported in the package of statistical data may be referred to herein as “oc-stats.” In some examples, the package of statistical data may also include details about clients connected to network device **500** and the associated client sessions. NMS agent **544** may then report the package of statistical data to NMS **130** in the cloud. In other examples, NMS **130** may request, retrieve, or otherwise receive the package of statistical data from network device **500** via an API, an open configuration protocol, or another of communication protocols. The package of statistical data created by NMS agent **544** or another module of network device **500** may include a header identifying network device **500** and the statistics and data samples for each of the logical paths from network device **500**. In still other examples, NMS agent **544** reports event data to NMS **130** in the cloud in response to the occurrence of certain events at network device **500** as the events happen. The event-driven data may be referred to herein as "oc-events."

[0109] In some examples, network device **500** includes device localization module **536**. Device localization module **536** of network device **500** may include an example or alternative implementation of device localization module **236** of FIG. **2** or device localization module **336** of FIG. **3**.

[0110] FIG. **6** illustrates an example of determining a location of a target device based on directional information of signals, in accordance with one or more techniques of this disclosure. In the example of FIG. **6**, devices **600** may include devices **600**A-**600**E (collectively referred to herein as "devices **600**"). Site **602** and devices **600**A-**600**E of FIG. **6** may include example or alternative implementations of sites **102** and APs **142** of FIG. **1**A. Devices **600** may include example or alternative implementations of UEs **148** are other devices at site **602**. FIG. **6** may be discussed with respect to FIG. **1**A, for example purposes only.

[0111] In the example of FIG. **6**, device **600**A, device **600**B, and device **600**C (collectively referred to herein as "reference devices **600**A-C") may have known positions at site **602** and device **600**D (referred to herein as "target device **600**D") may have an unknown position at site **602**. Reference devices **600**A-C and/or target device **600**D may determine distance measurements between devices **600**. For example, one or more of reference devices **600**A-C may send signals to target device **600**D, such as WI-FI signals at a frequency of 5 GHZ, and may determine, for example, a RTT of the signals sent to and from target device **600**D. Based on the RTT of the signals sent to and from target device **600**D, the reference devices **600**A-C may apply a localization algorithm, such as multilateration techniques, to determine a location of target device **600**D. In some instances, target device **600**D and/or reference devices **600**A-C may send distance measurements (e.g., RTT data) to NMS **130**.

[0112] In the example of FIG. **6**, target device **600**D is represented as two possible positions indicated by **600**D-**1** and **600**D-**2**, where the possible positions of **600**D-**1** and **600**D-**2** are equidistant or near equidistant to the reference devices **600**A-**600**C. In other words, target device **600**D is illustrated as located in one of possible position **600**D-**1** or possible position **600**D-**2**. Reference devices **600**A-**600**C may determine that a distance to target device **600**D may equally apply to a first position (as illustrated by **600**D-**1**) and a second position (as illustrated by **600**D-**2**).

[0113] NMS **130** may determine that device **600**D has two possible positions. For example, NMS **130** may obtain directional information of a signal communicated between reference device **600**A and target device **600**D. NMS **130** may compare the directional information of the signal communicated between reference device **600**A and target device **600**D (e.g., signal received by reference device **600**A from target device **600**D in the north-east direction) with an expected positional direction of target device **600**D relative to reference device **600**A (e.g., south-east direction) and determines that the directional information of the signal communicated between device **600**A and target device **600**D is inconsistent with the expected positional direction of target device **600**D relative to reference device **600**A. NMS **130** generates a flag indicating the discrepancy in direction of position **600**D-**1** relative to device **600**A. Similarly, NMS **130** may obtain directional information of a signal communicated between reference device **600**B and target device **600**D. NMS **130** may compare the directional information of the signal communicated between reference device **600**B and target device **600**D (e.g., signal received by reference device

600B from target device **600**D in the north-east direction) with an expected positional direction of target device **600**D relative to reference device **600**B (e.g., south-west direction) and determines that the directional information of the signal communicated between reference device **600**B and target device **600**D is inconsistent with the expected positional direction of target device **600**D relative to reference device **600**B. NMS **130** generates a flag indicating the discrepancy in direction of position **600**D-**1** relative to device **600**B. NMS **130** continues the process of identifying discrepancies in the direction of target device **600**D relative to other reference devices. NMS **130** may compute a number of flags (e.g., three) and compare the number of flags to a threshold. If the threshold is satisfied, NMS **130** may determine that the localization of devices **600** has an error (e.g., that device **600**D has two possible positions).

[0114] In some examples, NMS **130** may generate a distribution of possible positions of target device **600**D based on the distance measurements between devices **600**. NMS **130** may determine that the localization of devices **600** has an error (e.g., that device **600**D has two possible positions) based on a determination of whether the distribution of possible positions of target device **600**D forms a multimodal distribution, such as a multimodal distribution with a first local maxima indicative of first position **600**D-**1** and a second local maxima indicative of second position **600**D-**2**.

[0115] NMS **130** may determine a candidate position of target device **600**D based on the directional information of directional beams communicated between reference devices **600**A-**600**C and target device **600**D. Reference devices **600**A-**600**C and target device **600**D may send directional beams, or a set of directional beams using directional antennas. Reference devices **600**A-**600**C and target device **600**D may each listen for directional beams from other devices. Reference devices **600**A-C and target device **600**D may listen, for example, for a beam with the highest signal strength (referred to herein as the loudest or strongest directional beam) from another device and assign the other device an orientation relative to a direction of the device that sent the loudest directional beam. In the example of FIG. **6**, NMS **130** may receive directional information indicative of reference device **600**A receiving a loudest directional beam from target device **600**D at a particular angle in the east direction. Similarly, NMS **130** may receive directional information indicative of reference device **600**B receiving a loudest directional beam from target device **600**D at a particular angle in the north-east direction, and/or receive directional information indicative of reference device **600**C receiving a loudest directional beam from target device **600**D at a particular angle in the north direction. In some examples, reference devices **600**A-C may each receive a plurality of loud directional beams from another device and the plurality of loud directional beams may be normalized. Based on the directional information indicating the direction in which the reference devices **600**A-C receive the loudest directional beams from target device **600**D, NMS **130** may determine target device **600**D is in the position indicated by **600**D-**2**.

[0116] In some examples, NMS **130** may additionally, or alternatively, determine the location of target device **600**D based on the direction in which target device **600**D receives the loudest directional beams from reference devices **600**A-C. For example, NMS **130** may determine target device **600**D is in the north-east direction indicated by position **600**D-**2** based on a direction in which target device **600**D receives a loudest directional beam from one or more of reference devices **600**A-C. For example, NMS **130** may receive directional information indicative of target device **600**D receiving a loudest directional beam from reference device **600**A at a particular angle in the west direction. Similarly, NMS **130** may receive directional information indicative of reference device **600**B receiving a loudest directional beam from reference device **600**B at a particular angle in the south-west direction, and/or receive directional information indicative of reference device **600**C receiving a loudest directional beam from reference device **600**C at a particular angle in the south direction. Based on the directional information indicating the direction in which the target device **600**D receives the loudest directional beams from reference devices **600**A-C, NMS **130** may determine target device **600**D is in the east of reference device **600**A, north-east of reference device **600**B, and north of reference device **600**C.

[0117] In some examples, NMS **130** may eliminate possible positions based on the directional information indicating the direction in which the reference devices **600**A-**600**C and/or target device **600**D receives the loudest directional beams from other APs. For example, NMS **130** may eliminate position **600**D-**1** as a possible position of target device **600**D based on directional information indicative of reference devices **600**A-C and/or target device **600**D receiving the loudest directional beams from a direction that is inconsistent with the location of position **600**D-**1**.

[0118] In some examples, NMS **130** may obtain information from devices that are proximate to a possible position of target device **600**D as indicated by **600**D-**1**, such as device **600**E. In the example of FIG. **6**, NMS **130** may obtain information indicative of whether device **600**E detects a signal from target device **600**D. For example, NMS **130** may eliminate position **600**D-**1** as a possible position of device **600**D if device **600**E does not detect a signal from a device located at position indicated by **600**D-**1**, thus making position **600**D-**2** a more likely position of target device **600**D. NMS **130** may use the determination by device **600**E to confirm that position **600**D-**2** is the correct position of target device **600**D, and that the determination by device **600**E does not conflict with the directional information of signals communicated between reference devices **600**A-**600**C and target device **600**D.

[0119] FIG. **7** illustrates an example of determining a location of a target device with limited reference devices based on directional information of signals, in accordance with one or more techniques of this disclosure. In the example of FIG. **7**, site **702** may include devices **700**A, **700**B, and device **700**D (collectively referred to herein as “devices **700**”). Site **702** and devices **700** of FIG. **7** may include example or alternative implementations of sites **102** and APs **142** of FIG. **1**A. Devices **700** may include example or alternative implementations of UEs **148** of FIG. **1**A. FIG. **7** may be discussed with respect to FIG. **1**A, for example purposes only.

[0120] In the example of FIG. **7**, device **700**A and device **700**B (collectively referred to herein as “reference devices **700**A-**700**B”) may have known positions at site **702** and device **700**D (referred to herein as “target device **700**D”) may have an unknown position at site **702**. NMS **130** may determine a location of target device **700**D at site **702**. In the example of FIG. **7**, reference devices **700**A-**700**B may be the only reference devices available to determine the location of target device **700**D. One or more of reference devices **700**A-**700**B may send signals to target device **700**D, such as WI-FI signals at a frequency of 5 GHZ, and may determine, for example, a RTT of the signals sent to and from target device **700**D. Based on the RTT of the signals sent to and from device **700**D, the reference devices **700**A-**700**B may apply a localization algorithm, such as multilateration techniques, to determine a location of target device **700**D. In these examples, if target device **700**D is an isolated device where there are less than three distance measurements (e.g., a first distance measurement between reference device **700**A and target device **700**D and a second distance measurement between reference device **700**B and target device **700**D) to determine the location of target device **700**D, the determination of the location of target device **700**D may result in two possible positions as indicated by **700**D-**1** and **700**D-**2**, where the possible positions **700**D-**1** and **700**D-**2** are equidistant or near equidistant to the reference devices **700**A-**700**B. In other words, reference devices **700**A-**700**B may determine, from the limited number of distance measurements, that a distance to target device **700**D may equally apply to a first possible position (as illustrated by **700**D-**1**) and a second possible position (as illustrated by **700**D-**2**).

[0121] NMS **130** may determine that target device **700**D is an isolated device based on whether there are less than three distance measurements (e.g., a first distance measurement between reference device **700**A and target device **700**D and a second distance measurement between reference device **700**B and target device **700**D). In response to determining that target device **700**D is an isolated device, NMS **130** may determine a candidate position of target device **700**D based on the directional information of directional beams communicated between reference devices **700**A-**700**B and target device **700**D. For example, NMS **130** may obtain directional information indicative of reference device **700**A receiving a directional beam from target device **700**D at a particular angle in the south-east direction relative to reference device **700**A. Similarly, NMS **130** may obtain directional information indicative of reference device **700**B receiving a directional beam from target device **700**D at a particular angle in the south direction relative to reference device **700**B. Additionally, or alternatively, NMS **130** may obtain directional information indicative of target device **700**D receiving a directional beam from reference device **700**A at a particular angle in the north-west direction relative to target device **700**D. Similarly, NMS **130** may obtain directional information indicative of target device **700**D receiving a directional beam from reference device **700**B at a particular angle in the north direction relative to target device **700**D.

[0122] NMS **130** may determine whether the directional information of signals communicated between reference devices **700**A-**700**B and target device **700**D deviate from a direction in which reference devices **700**A-**700**B are expected to receive a signal from target device **700**D. For example, if reference device **700**A is expected to receive a directional beam from target device **700**D at a particular angle in the north-west direction (e.g., as indicated by position **700**D-**1**), but NMS **130** determines that the directional information of the signal communicated between reference device **700**A and target device **700**D is indicative of reference device **700**A receiving a directional beam from target device **700**D at a particular angle in the south-east direction, NMS **130** may eliminate (e.g., by applying an error bias) position **700**D-**1** as a candidate position of target device **700**D. Similarly, if reference device **700**B is expected to receive a directional beam from target device **700**D at a particular angle in the north-west direction (e.g., as indicated by position **700**D-**1**), but NMS **130** determines that the directional information of the signal communicated between reference device **700**B and target device **700**D is indicative of reference device **700**B receiving a directional beam from target device **700**D at a particular angle in the south-east direction, NMS **130** may eliminate (e.g., by applying an error bias) position **700**D-**1** as a candidate position of target device **700**D.

[0123] FIG. **8** illustrates an example of determining a location of a device with a single reference device based on directional information of signals, in accordance with one or more techniques of this disclosure. In the example of FIG. **8**, site **802** may include devices **800**A-**800**D (collectively referred to herein as “devices **800**”). Site **802** and devices **800**A-**800**D of FIG. **8** may include example or alternative implementations of sites **102** and APs **142** of FIG. **1**A. FIG. **8** may be discussed with respect to FIG. **1**A, for example purposes only.

[0124] In the example of FIG. **8**, device **800**A (referred to herein as “reference device **800**”) may have a known position at site **802** and device **800**D (referred to herein as “target device **800**D”) may have an unknown position at site **802**. In this example, reference device **800**A may be the only reference device that may determine distance measurements, based on, for example, an FTM protocol, relative to target device **800**D (e.g., due to target device **800**D being in communication range of reference device **800**A). For example, devices **800**B and **800**C are unable to communicate 5 GHz Wi-Fi signals to target device **800**D, and thus are unable to determine the distance between device **800**B and target device **800**D or the distance between device **800**C and target device **800**D according to an FTM protocol, whereas reference device **800**A is able to communicate 5 GHz Wi-Fi signals to target device **800**D and may determine an estimated or expected location of target device **800**D according to the FTM protocol. Target device **800**D may be referred to herein as an isolated device because there is only a single reference device **800**A that can perform distance measurements of target device **800**D.

[0125] In this example, NMS **130** may determine a location of target device **800**D based on directional information of signals communicated between devices **800**A-**800**C and target device **800**D. For example, NMS **130** may further refine the location of target device **800**D based on directional information of signals communicated between devices **800**B and target device **800**D and/or between devices **800**C and target device **800**D. As described above, the signals communicated between devices **800**A-**800**C and target device **800**D may include BLE signals or other signals communicated at a lower frequency (e.g., a WI-FI signal communicated at 2.4 GHz) and may reach farther distances. In the example of FIG. **8**, NMS **130** may obtain directional information of signals communicated between devices **800**A-**800**C and target device **800**D. NMS **130** may refine, based on the directional information of signals, the estimated location of target device **800**D to position window **888**.

[0126] NMS **130** may narrow down two or more possible positions of target device **800**D, determined based on distance measurements between reference device **800**A and target device **800**D, to a candidate position represented as position window **888**. NMS **130** may determine position window **888** by narrowing down a probability band specifying two or more possible positions of target device **800**D (e.g., a probability band around target device **800**D determined based on distance measurements between reference device **800**A and target device **800**D, as well as based on directional information of signals communicated between reference device **800**A and target device **800**D, as illustrated by probability band **886**). Position window **888** may be a reduced version of probability band **886** specifying a likely location of target device **800**D based on directional information between target device **800**D and devices **800**A-C. In some instances, NMS **130** may determine position window **888** as a candidate position based on directional information of signals communicated between reference device **800**A and target device **800**D. In some examples, NMS **130** may add a weight to directional information of signals communicated between devices **800**A-**800**C and target device **800**D. NMS **130** may determine a candidate position as position window **888** based on the weights added to the directional information. For example, NMS **130** may determine position window **888** as a range of likely positions based on the intersection of directional beams target device **800**D received from devices **800**A-**800**C.

[0127] FIG. **9** is a flow chart illustrating an example operation for localization of devices at a site, in accordance with one or more techniques of this disclosure. FIG. **9** may be discussed with respect to FIG. **1**A for example purposes only.

[0128] NMS **130** may obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site (**902**). For example, the at least one reference device may send a signal (e.g., a 5 GHz signal) to the target device to determine distance measurements between the target device and the at least one reference device according to a FTM protocol. In this example, NMS **130** may obtain the distance measurements from the at least one reference device.

[0129] NMS **130** may obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device (**904**). For example, NMS **130** may obtain directional information from the at least one reference device specifying a direction an antenna of the at least one reference device received a loudest BLE signal from the target device. Alternatively, or additionally, NMS **130** may obtain directional information from the target device specifying a direction an antenna of the target received a loudest BLE signal from the at least one reference device.

[0130] NMS **130** may determine, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device (**906**). NMS **130** may check for discrepancies between an expected positional direction of the target device relative to the at least one reference device and the directional information of signals communicated between the at least one reference device and the target device and may flag any discrepancies. Responsive to NMS **130** determining a number of flagged discrepancies satisfies a threshold (e.g., a predefined number of flags), NMS **130** may trigger a correction process to resolve a localization error (e.g., flip ambiguity) associated with the expected direction. In some examples, NMS **130** may, alternatively or additionally, trigger the correction process by determining, based on the distance measurements, a probability distribution of possible positions of the target device is multimodal, such that local maxima of the probability distribution represent the two or more possible positions. NMS **130** may initiate the correction process by creating a multimodal distribution of the possible positions and applying error biases to possible positions based on the directional information.

[0131] NMS **130** may determine, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device (**908**). For example, NMS **130** may determine the candidate position of the target device by selecting a local maxima from the multimodal distribution with the least amount of error bias. In some instances, NMS **130** may cluster possible positions (e.g., local maxima from the multimodal distribution) by grouping possible positions that or similar or nearby to each other. NMS **130** may eliminate possible positions (e.g., local maxima or clustered local maxima from the multimodal distribution) based on the error bias until one or more possible positions with the least amount of error bias remains. NMS **130** may determine one or more candidate positions as the one or more remaining possible positions. NMS **130** may reorient the target device based on the one or more candidate positions. In instances where NMS **130** determines multiple candidate positions, NMS **130** may determine whether there are discrepancies between the directional information and the direction the target device is from the at least one reference device based on an expected direction of each of the candidate positions. NMS **130** may place a user interface element indicating a location of the target device on the site map based on the candidate position with the fewest number of flagged discrepancies.

[0132] The techniques described herein may be implemented in hardware, software, firmware, or any combination thereof. Various features described as modules, units or components may be implemented together in an integrated logic device or separately as discrete but interoperable logic devices or other hardware devices. In some cases, various features of electronic circuitry may be implemented as one or more integrated circuit devices, such as an integrated circuit chip or chipset.

[0133] If implemented in hardware, this disclosure may be directed to an apparatus such as a processor or an integrated circuit device, such as an integrated circuit chip or chipset. Alternatively, or additionally, if implemented in software or firmware, the techniques may be realized at least in part by a computer-readable data storage medium comprising instructions that, when executed, cause a processor to perform one or more of the methods described above. For example, the computer-readable data storage medium may store such instructions for execution by a processor.

[0134] A computer-readable medium may form part of a computer program product, which may include packaging materials. A computer-readable medium may comprise a computer data storage medium such as random access memory (RAM), read-only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), Flash memory, magnetic or optical data storage media, and the like. In some examples, an article of manufacture may comprise one or more computer-readable storage media.

[0135] In some examples, the computer-readable storage media may comprise non-transitory media. The term “non-transitory” may indicate that the storage medium is not embodied in a carrier wave or a propagated signal. In certain examples, a non-transitory storage medium may store data that can, over time, change (e.g., in RAM or cache).

[0136] The code or instructions may be software and/or firmware executed by processing circuitry including one or more processors, such as one or more digital signal processors (DSPs), general purpose microprocessors, application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), or other equivalent integrated or discrete logic circuitry. Accordingly, the term “processor,” as used herein may refer to any of the foregoing structure or any other structure suitable for implementation of the techniques described herein. In addition, in some aspects, functionality described in this disclosure may be provided within software modules or hardware modules.

Claims

1. A network management system comprising: memory; and one or more processors in communication with the memory and configured to: obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site; obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device; determine, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device; and determine, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device.
2. The network management system of claim 1, wherein to determine the candidate position from the two or more possible positions of the target device relative to the at least one reference device, the one or more processors are configured to: determine a multimodal distribution of the two or more possible positions of the target device; apply a bias to at least one of the two or more possible positions based on the directional information; and determine the candidate position based on applying the bias to at least one of the two or more possible positions based on the directional information.
3. The network management system of claim 1, wherein to determine the candidate position from the two or more possible positions of the target device relative to the at least one reference device, the one or more processors are configured to: determine a probability window as the candidate position based on the directional information.
4. The network management system of claim 1, wherein to determine the two or more possible positions of the target device relative to the at least one reference device, the one or more processors are configured to: determine a discrepancy between a first direction indicative of a positional direction of the target device and a second direction indicative of the direction of a signal of the one or more signals communicated between the at least one reference device and the target device, wherein the first direction is determined based on the distance measurements; and generate one or more flags based on the discrepancy.
5. The network management system of claim 4, wherein the one or more processors are further configured to: determine a number of the one or more flags; compare the number of the one or more flags to a threshold; and determine the candidate position based on determining that the number of flags satisfies the threshold.
6. The network management system of claim 1, wherein to determine the candidate position, the one or more processors are further configured to: eliminate a possible position from the two or more possible positions based on determining whether a proximate device to the target device detects a signal from the target device from the possible position.
7. The network management system of claim 1, wherein the one or more processors are further configured to place a user interface element indicating a location of the target device on a site map of the site based on the candidate position.
8. A method comprising: obtaining, by one or more processors, distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site; obtaining, by the one or more processors, directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device; determining, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device; and determining, based on the directional information, a candidate

position from the two or more possible positions of the target device relative to the at least one reference device.
9. The method of claim 8, wherein determining the candidate position from the two or more possible positions of the target device relative to the at least one reference device comprises: determining a multimodal distribution of the two or more possible positions of the target device; applying a bias to at least one of the two or more possible positions based on the directional information; and determining the candidate position based on applying the bias to at least one of the two or more possible positions based on the directional information.
10. The method of claim 8, wherein determining the candidate position from the two or more possible positions of the target device relative to the at least one reference device comprises: determining a probability window as the candidate position based on the directional information.
11. The method of claim 8, wherein determining the two or more possible positions of the target device relative to the at least one reference device comprises: determining a discrepancy between a first direction indicative of a positional direction of the target device and a second direction indicative of the direction of a signal of the one or more signals communicated between the at least one reference device and the target device, wherein the first direction is determined based on the distance measurements; and generating one or more flags based on the discrepancy.
12. The method of claim 11, further comprising: determining a number of the one or more flags; comparing the number of the one or more flags to a threshold; and determining the candidate position based on determining that the number of flags satisfies the threshold.
13. The method of claim 8, wherein determining the candidate position comprises: eliminating a possible position from the two or more possible positions based on determining whether a proximate device to the target device detects a signal from the target device from the possible position.
14. The method of claim 8, further comprising: placing a user interface element indicating a location of the target device on a site map of the site based on the candidate position.
15. Non-transitory computer-readable storage media comprising instructions that, when executed, cause one or more processors to: obtain distance measurements between at least two devices at a site, wherein the at least two devices comprise at least one reference device positioned at a known location at the site and a target device relative to the at least one reference device positioned at an unknown location at the site; obtain directional information specifying a direction of one or more signals communicated between the at least one reference device and the target device; determine, based on the distance measurements and the directional information, two or more possible positions of the target device relative to the at least one reference device; and determine, based on the directional information, a candidate position from the two or more possible positions of the target device relative to the at least one reference device.
16. The non-transitory computer-readable storage media of claim 15, wherein to determine the candidate position from the two or more possible positions of the target device relative to the at least one reference device, the instructions cause the one or more processors to: determine a multimodal distribution of the two or more possible positions of the target device; apply a bias to at least one of the two or more possible positions based on the directional information; and determine the candidate position based on applying the bias to at least one of the two or more possible positions based on the directional information.
17. The non-transitory computer-readable storage media of claim 15, wherein to determine the candidate position from the two or more possible positions of the target device relative to the at least one reference device, the instructions cause the one or more processors to: determine a probability window as the candidate position based on the directional information.
18. The non-transitory computer-readable storage media of claim 15, wherein to determine the two or more possible positions of the target device relative to the at least one reference device, the instructions cause the one or more processors to: determine a discrepancy between a first direction

indicative of a positional direction of the target device and a second direction indicative of the direction of a signal of the one or more signals communicated between the at least one reference device and the target device, wherein the first direction is determined based on the distance measurements; and generate one or more flags based on the discrepancy.

19. The non-transitory computer-readable storage media of claim 15, wherein to determine the candidate position, the instructions cause the one or more processors to: eliminate a possible position from the two or more possible positions based on determining whether a proximate device to the target device detects a signal from the target device from the possible position.

20. The non-transitory computer-readable storage media of claim 15, wherein the instructions further cause the one or more processors to: place a user interface element indicating a location of the target device on a site map of the site based on the candidate position.