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Lubas et al.

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(54) **SYSTEM AND METHOD FOR DISCOVERING THE TOPOLOGY OF DEVICES WITHIN A BUILDING AUTOMATION AND CONTROL SYSTEM**

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H05B 39/04 (2006.01)
G01J 1/06 (2006.01)
H05B 47/11 (2020.01)

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CPC **G01J 1/0242** (2013.01); **G01J 1/06** (2013.01); **H05B 39/041** (2013.01); **H05B 47/11** (2020.01)

(58) **Field of Classification Search**
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See application file for complete search history.

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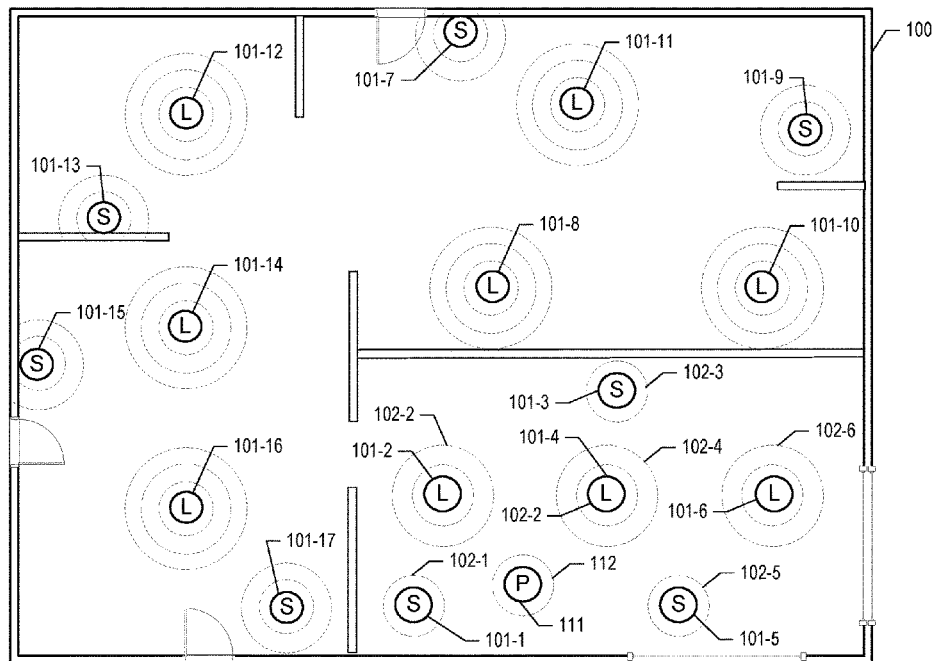
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(57) **ABSTRACT**

A method for discovering the topology of a connected lighting system. The method comprises: receiving a first measurement of a first light source in relation to a first sensor; receiving a second measurement of the first light source in relation to a second sensor; generating a first estimate of the position of the first light source, based on a first angle at the first sensor between (i) a first direction toward a current light source position and (ii) a second direction defined by the first measurement; generating a second estimate of the position of the first light source, based on a second angle at the second sensor between (i) a third direction toward the current light source position and (ii) a fourth direction defined by the second measurement; and generating an updated light source position of the first light source based on the first and second estimates.

9 Claims, 17 Drawing Sheets



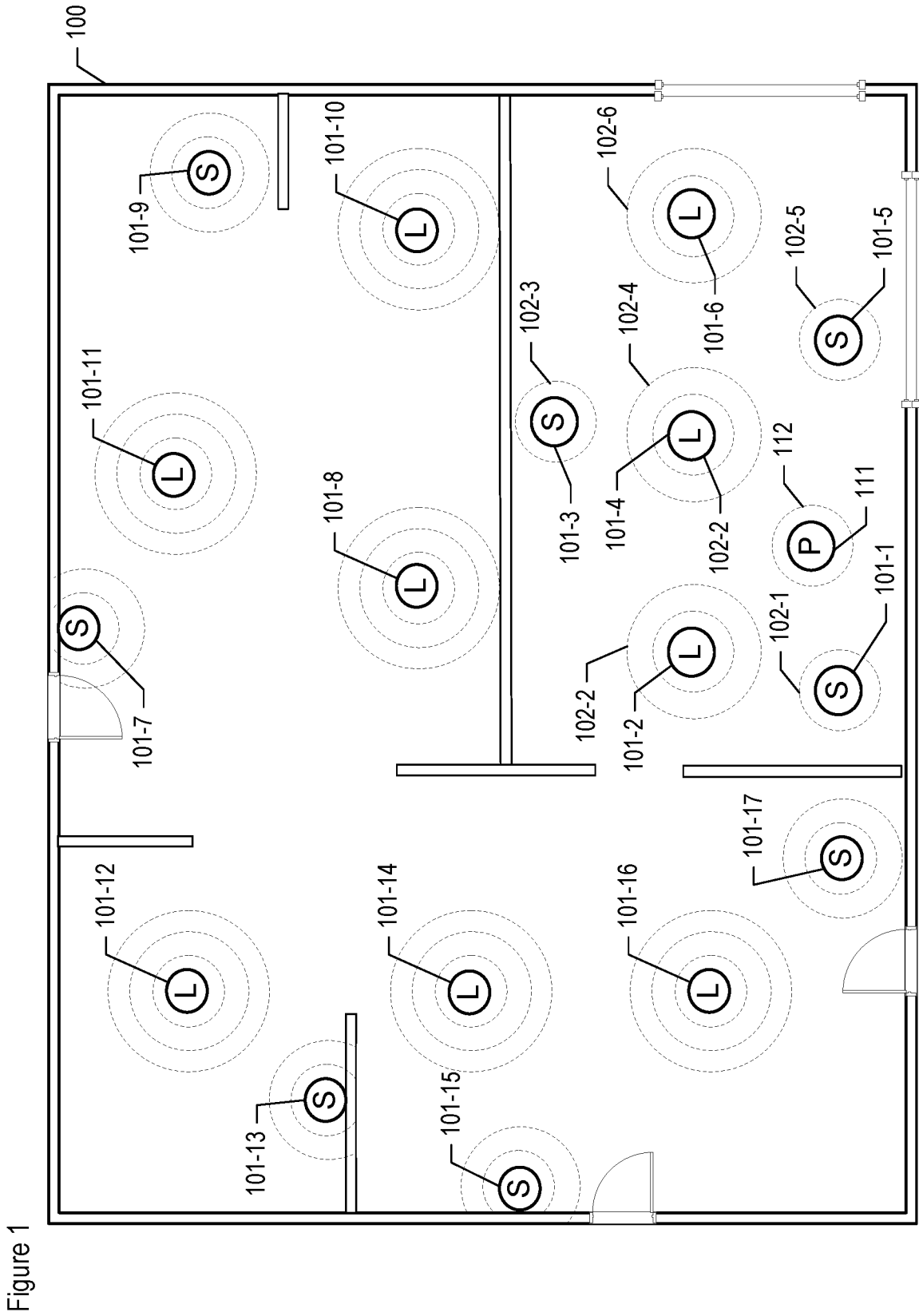


Figure 1

Figure 2

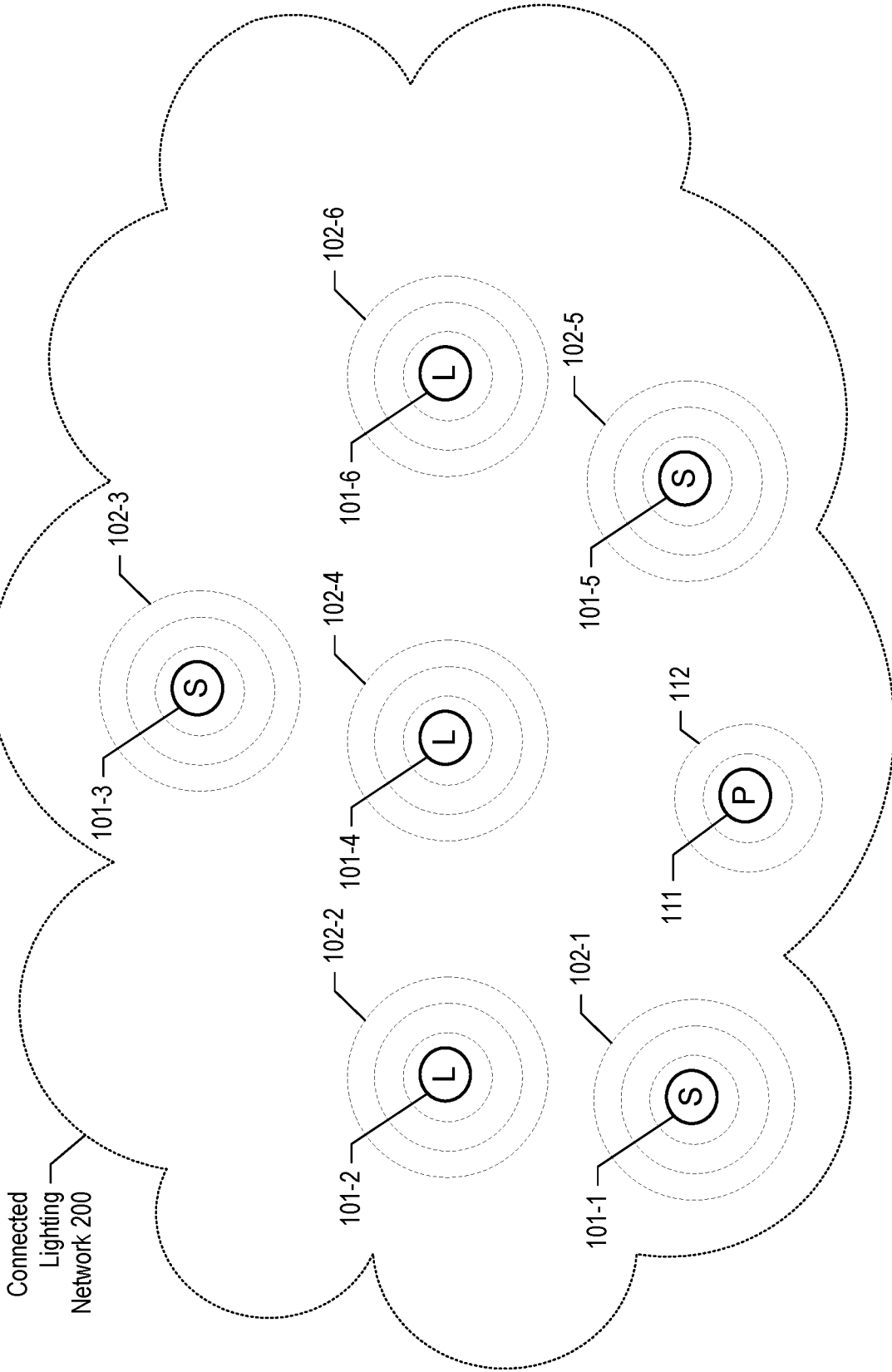


Figure 3

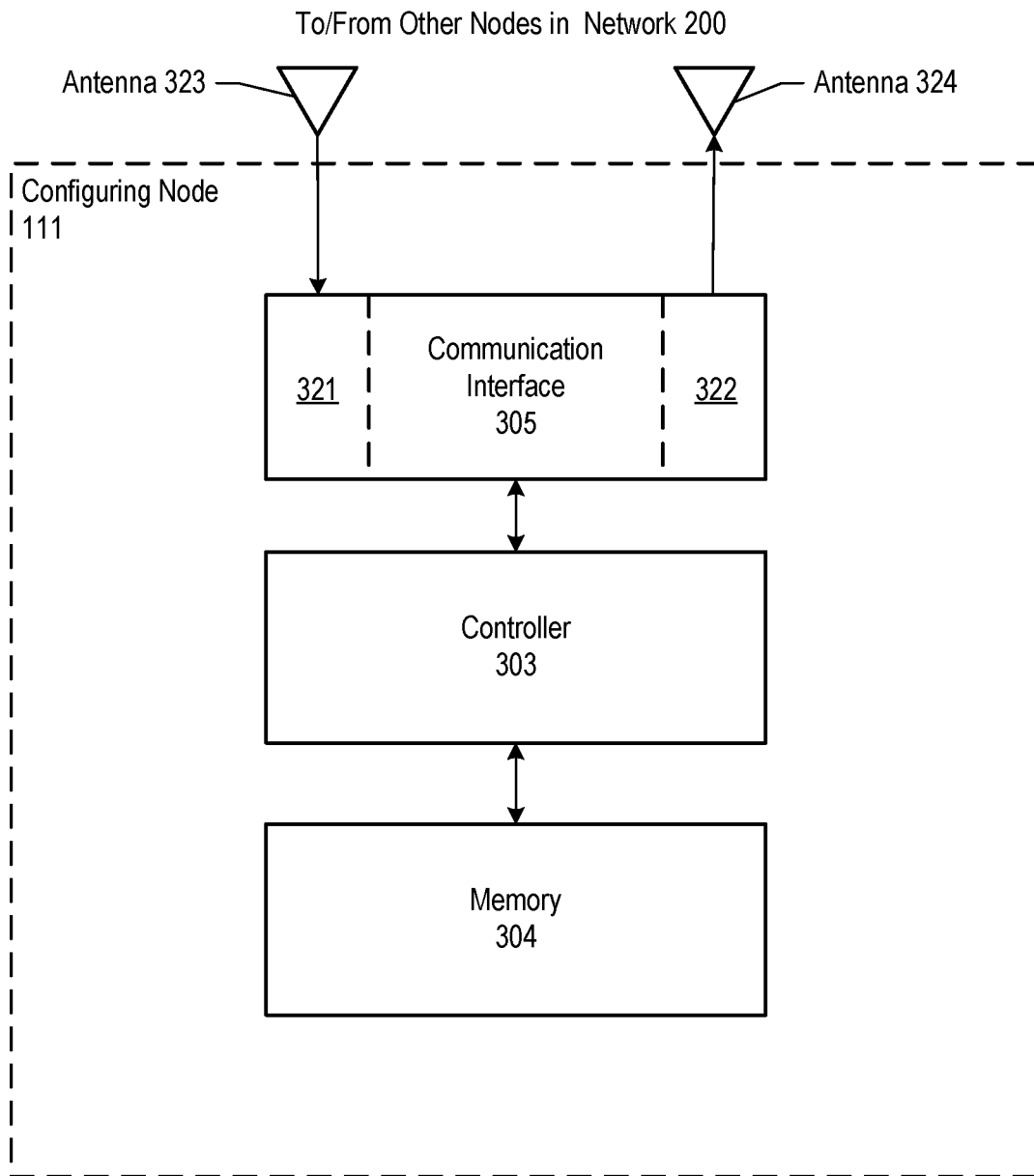


Figure 4

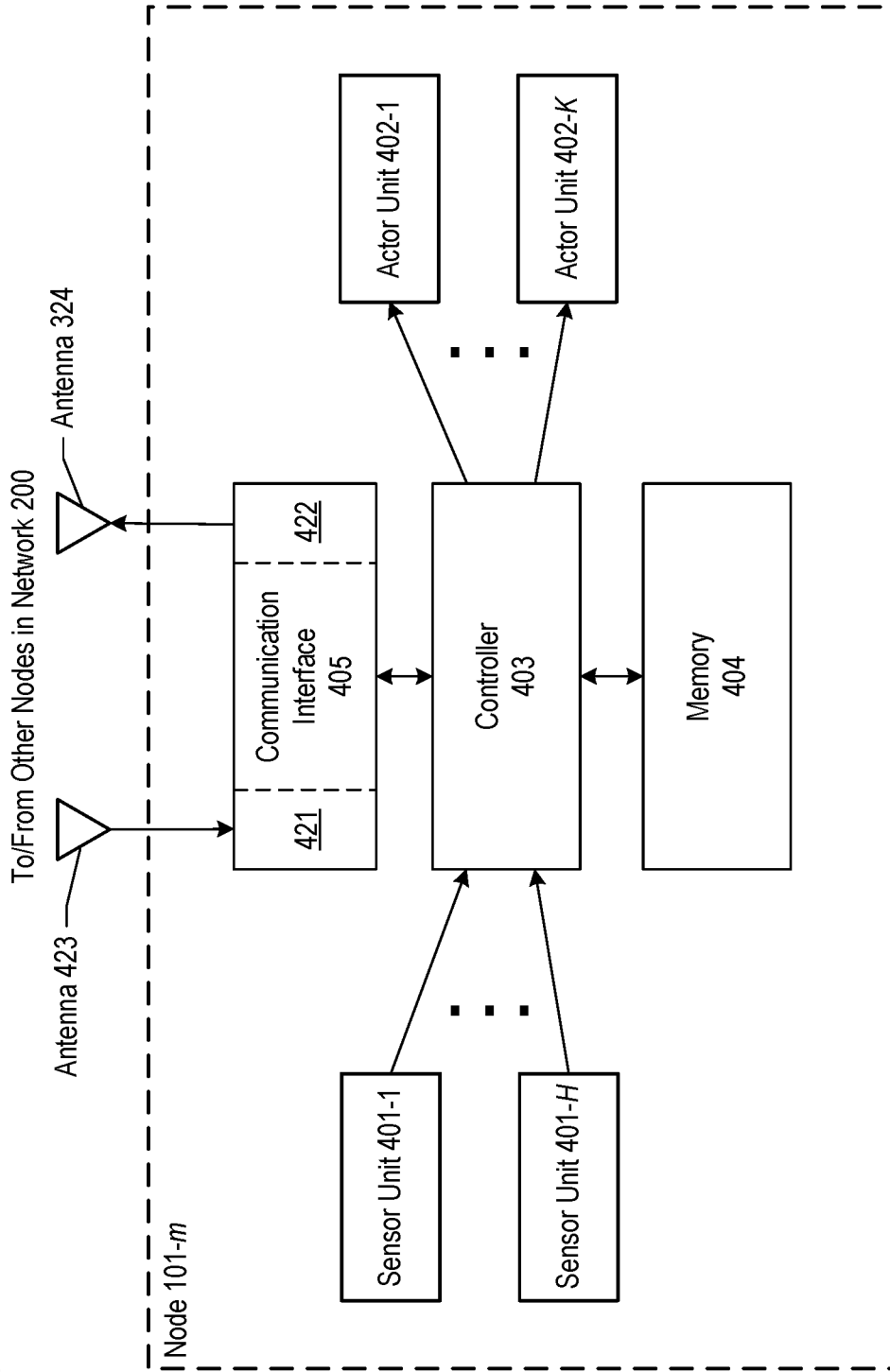


Figure 5

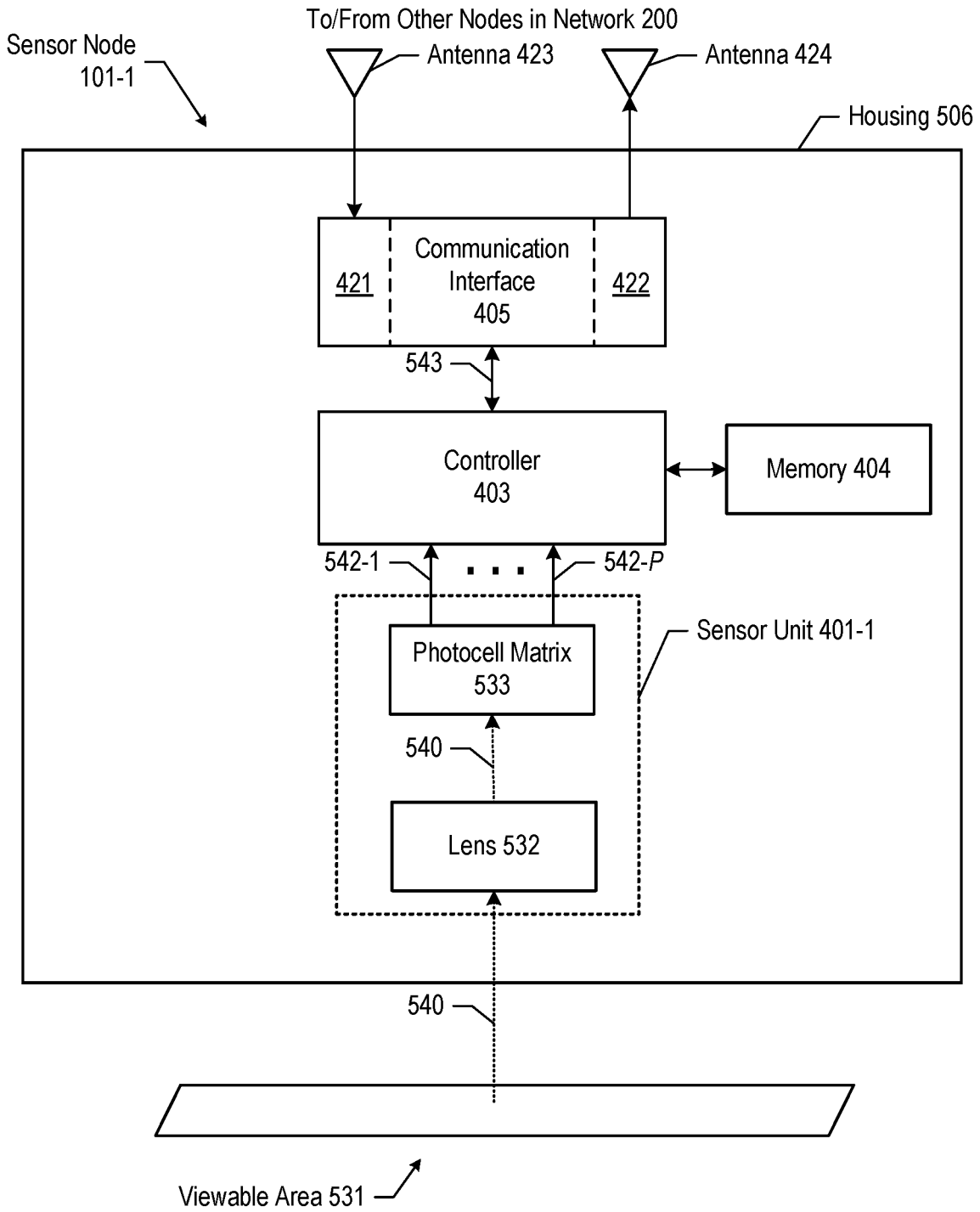


Figure 6

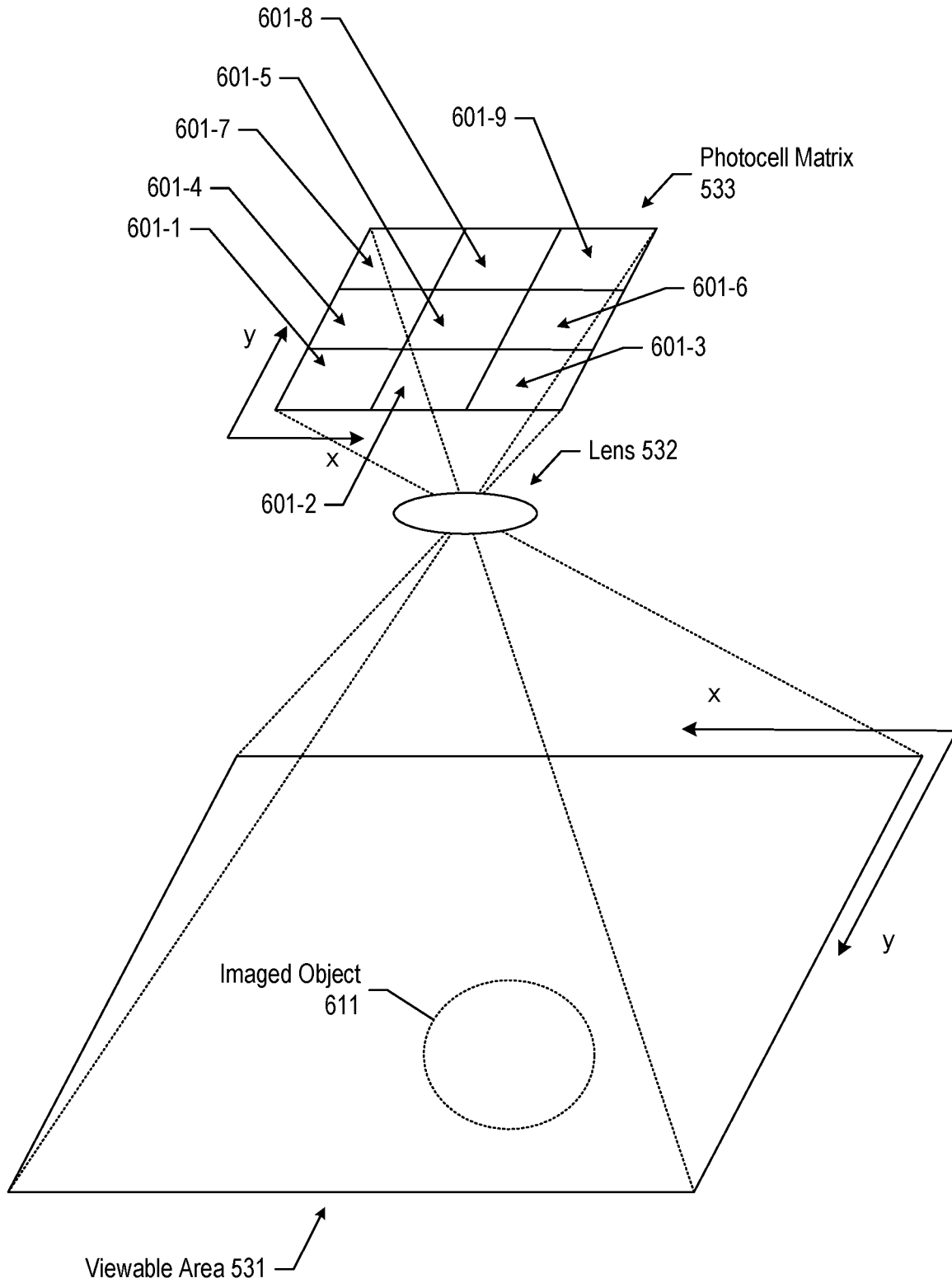
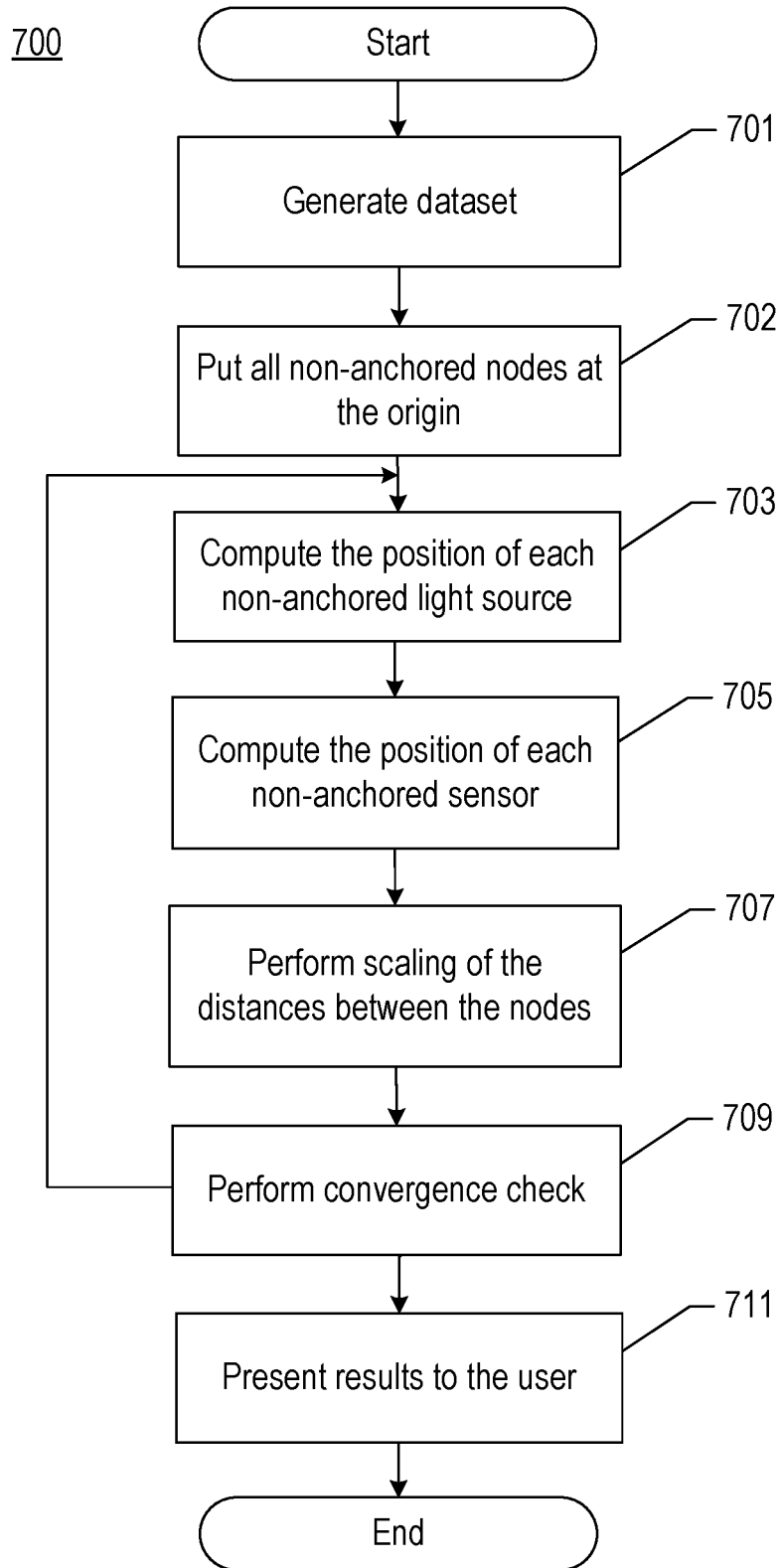


Figure 7



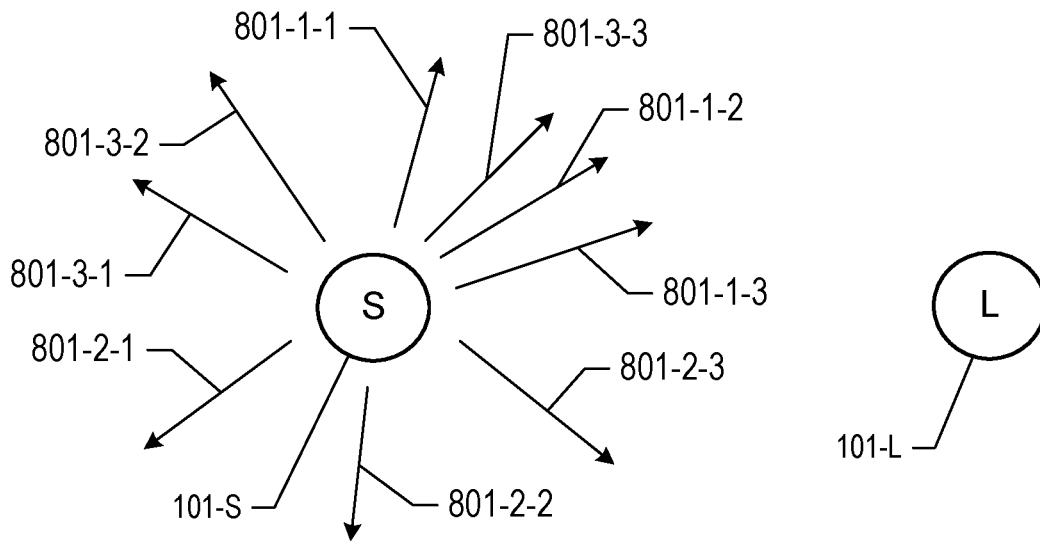


Figure 8A

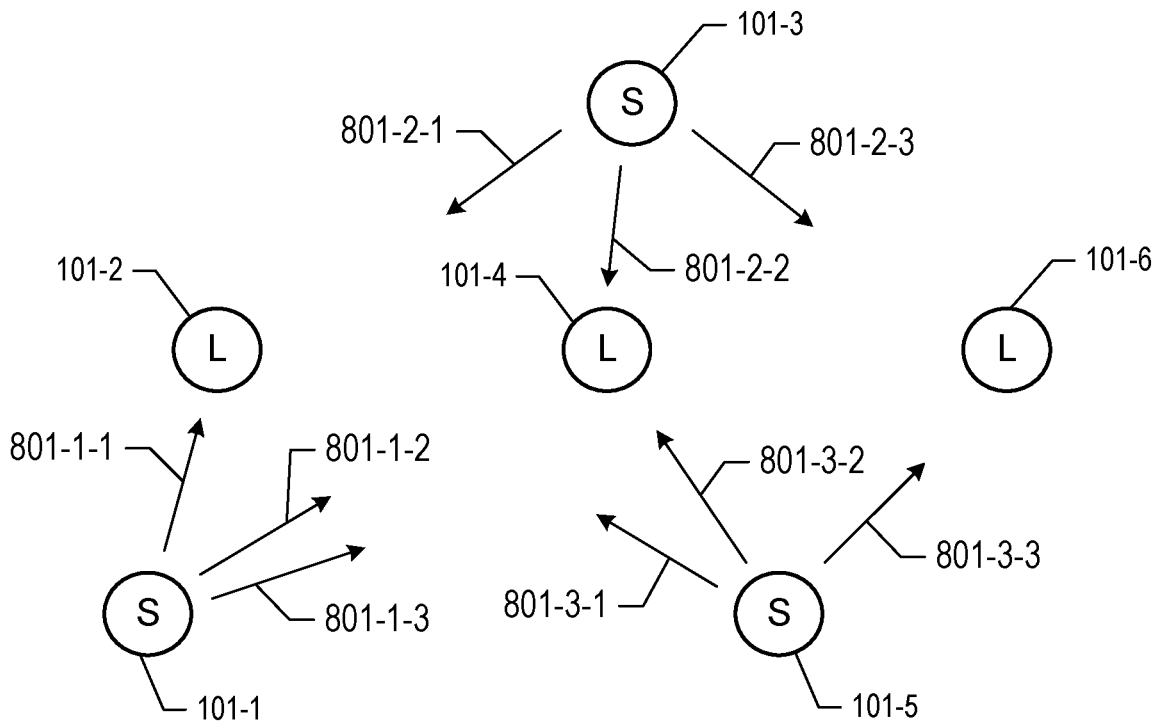


Figure 8B

Figure 9A

701

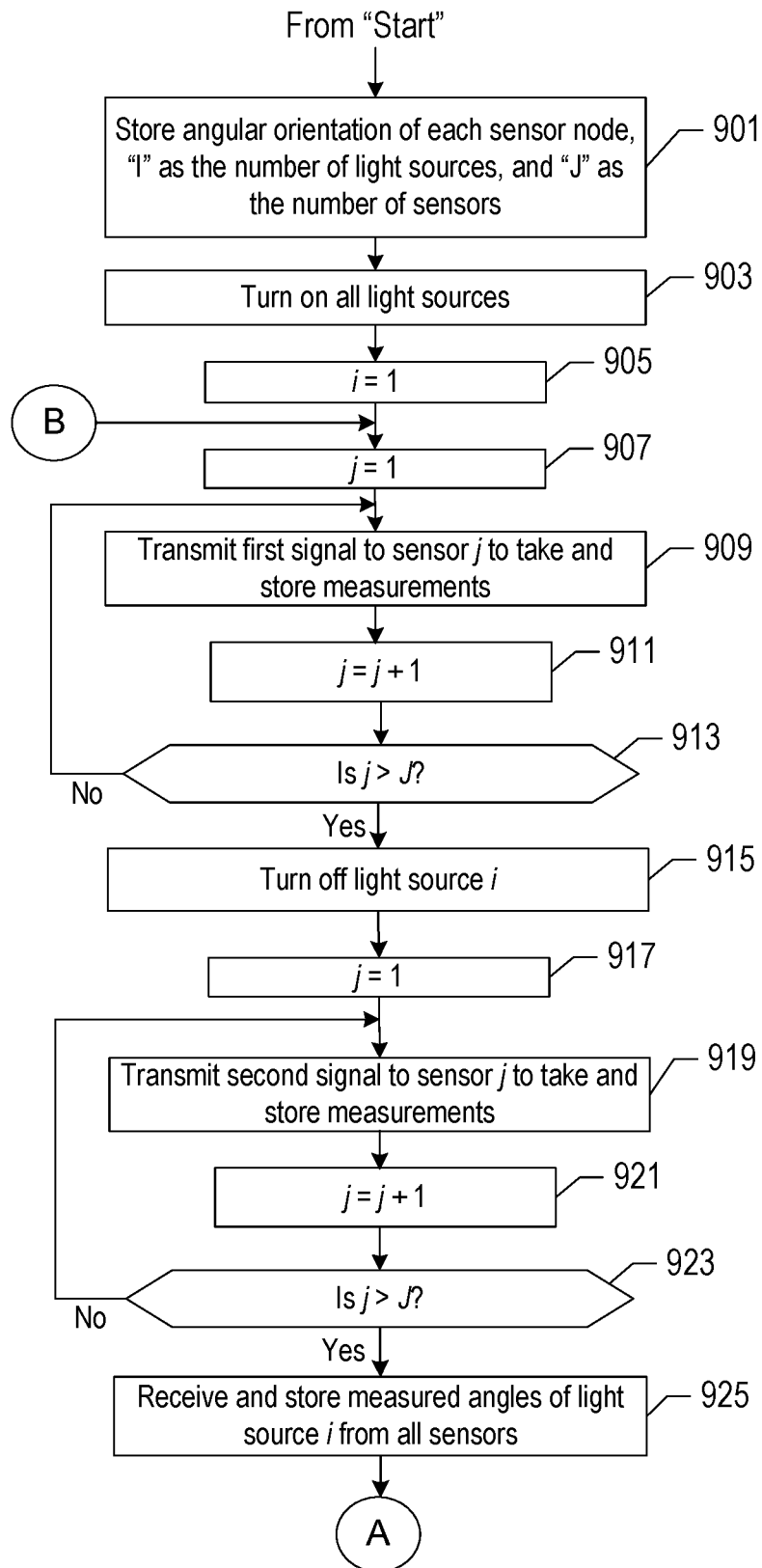


Figure 9B

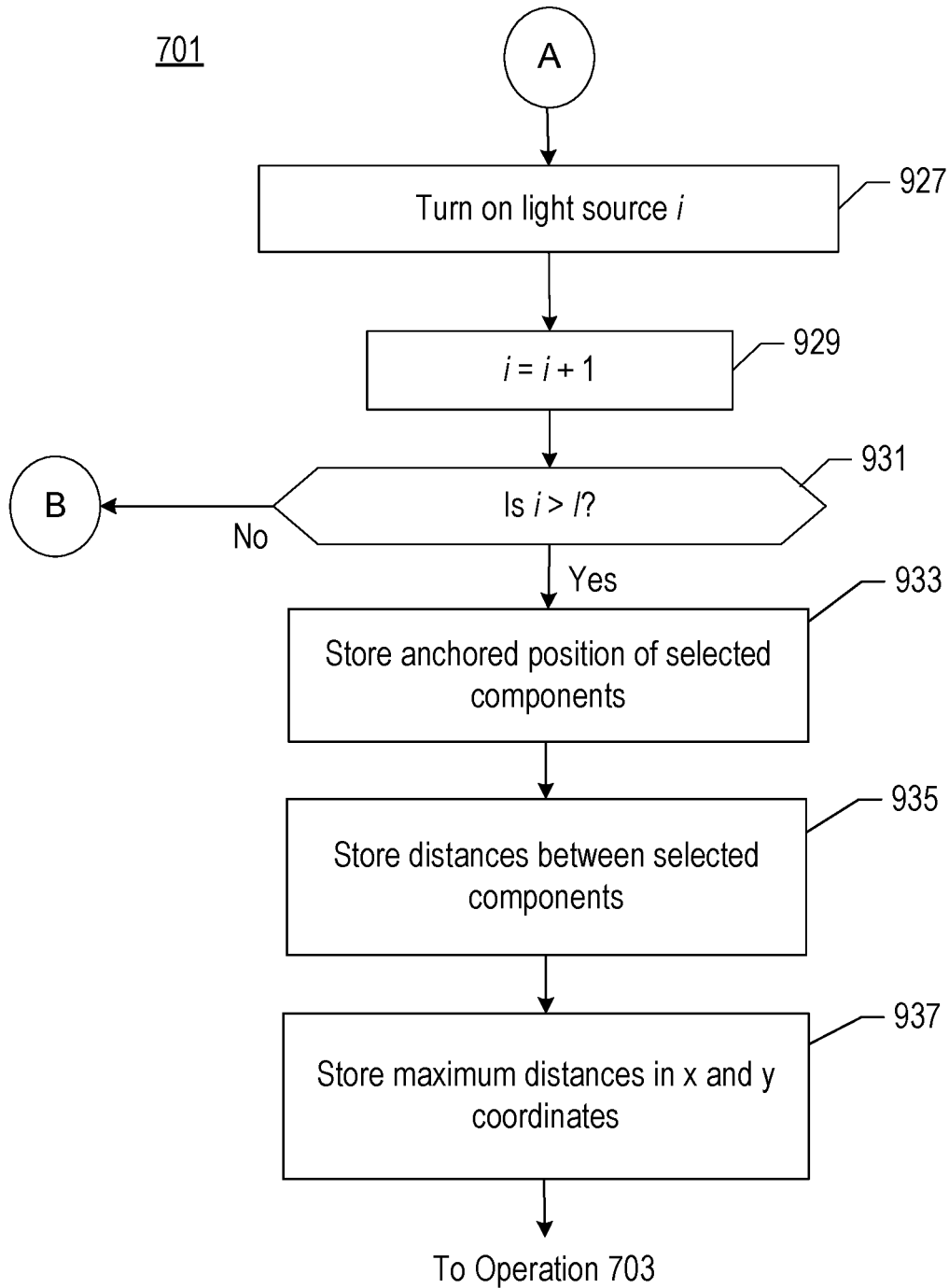


Figure 10

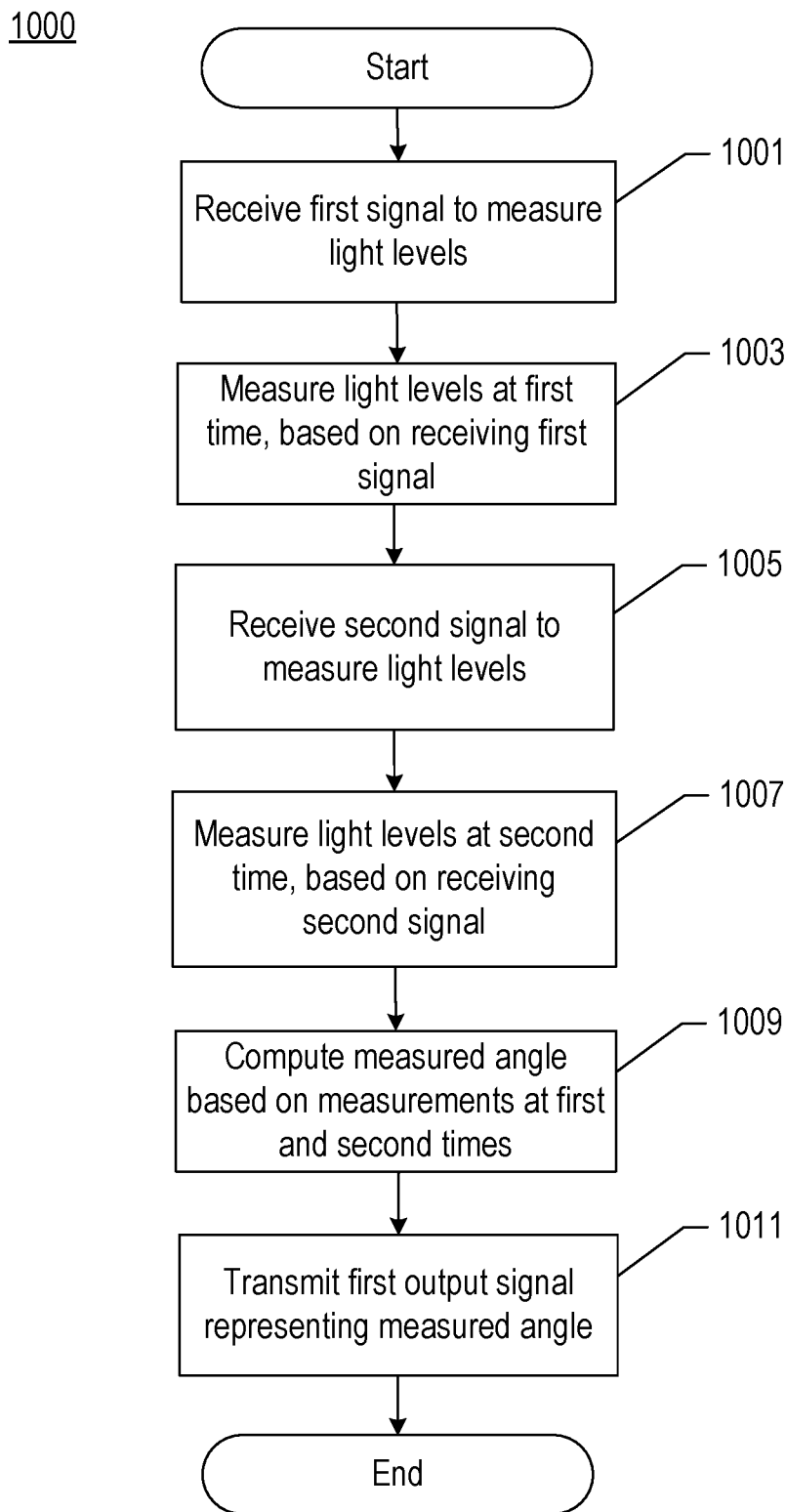


Figure 11

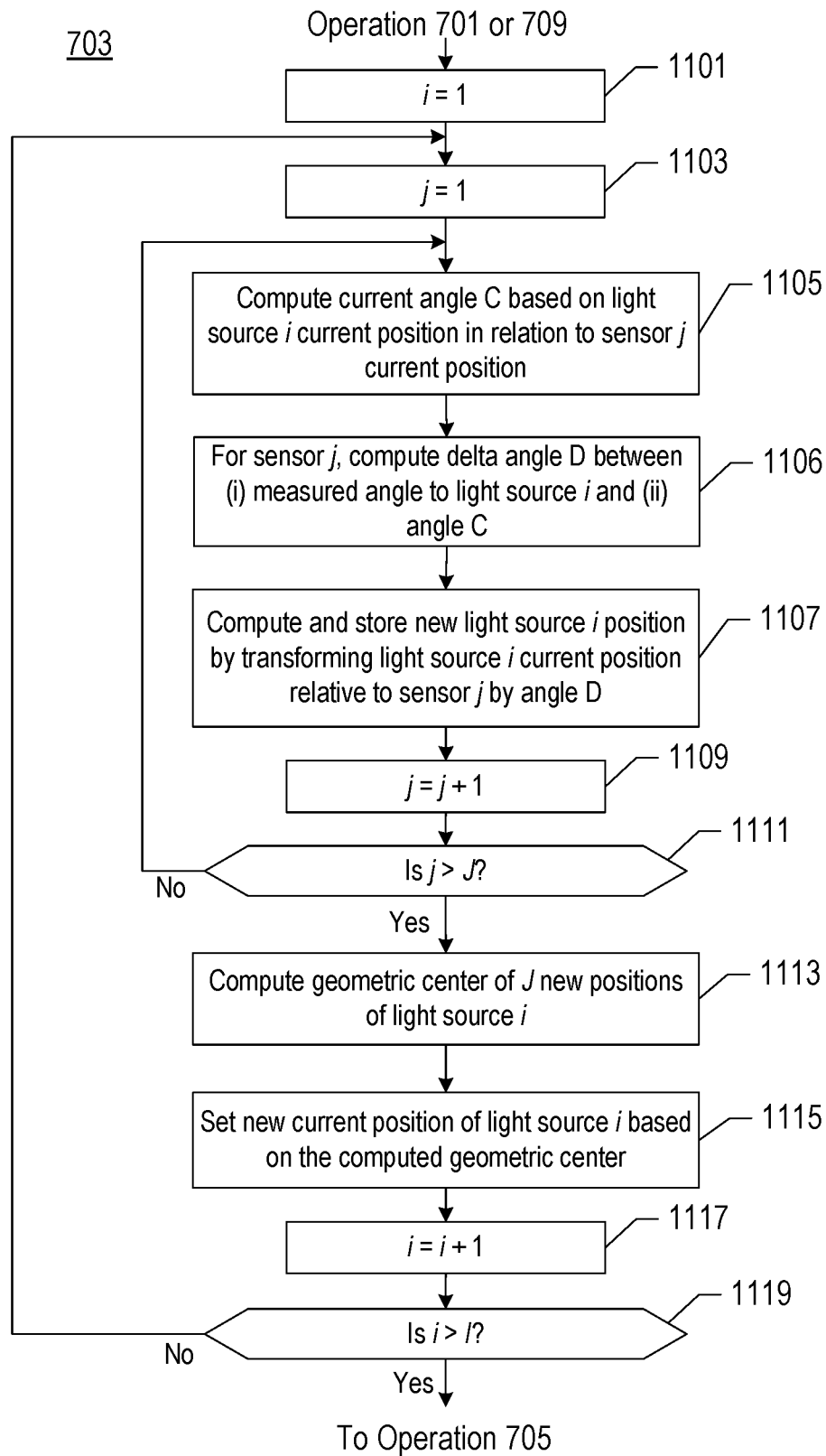


Figure 12

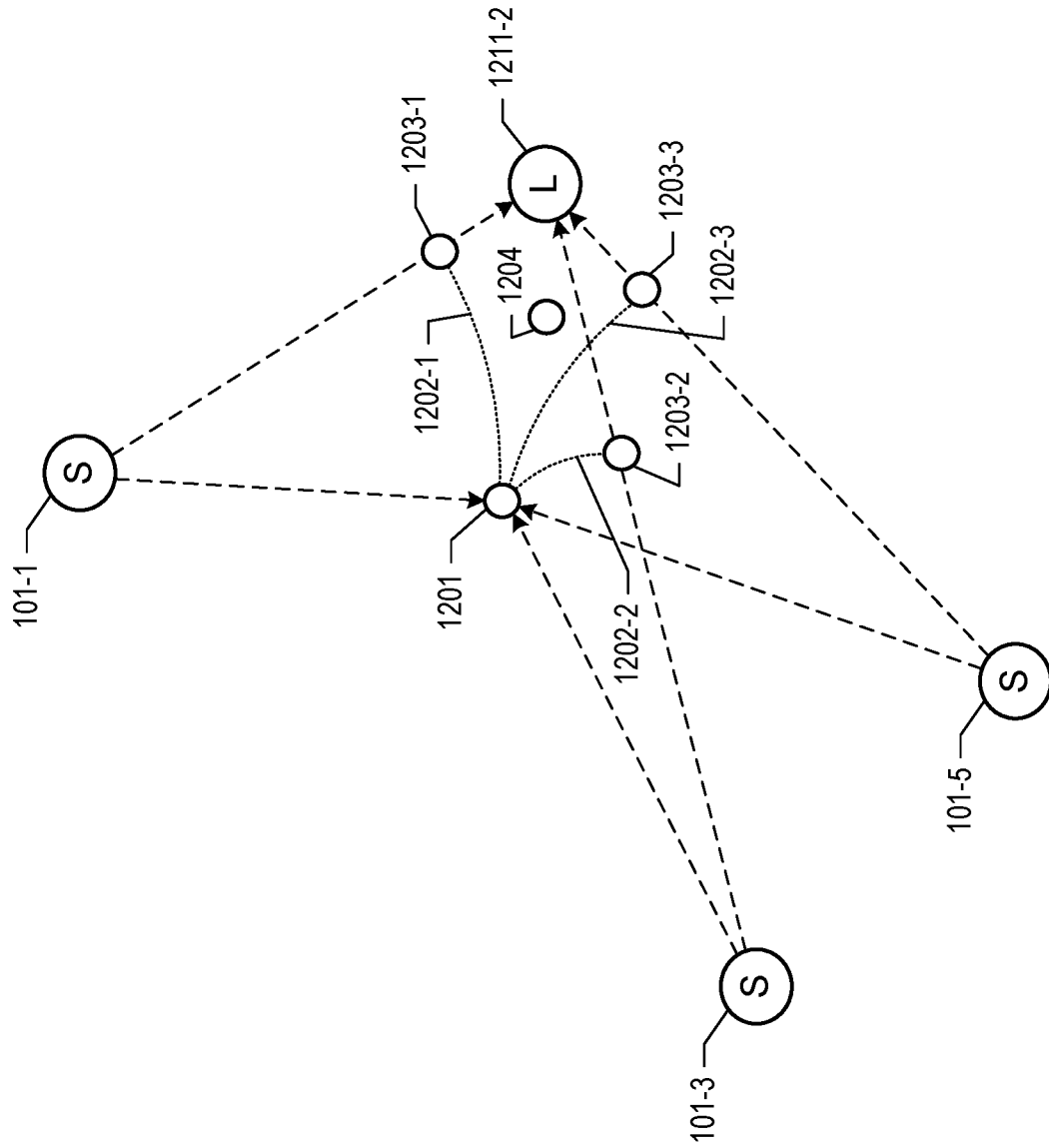
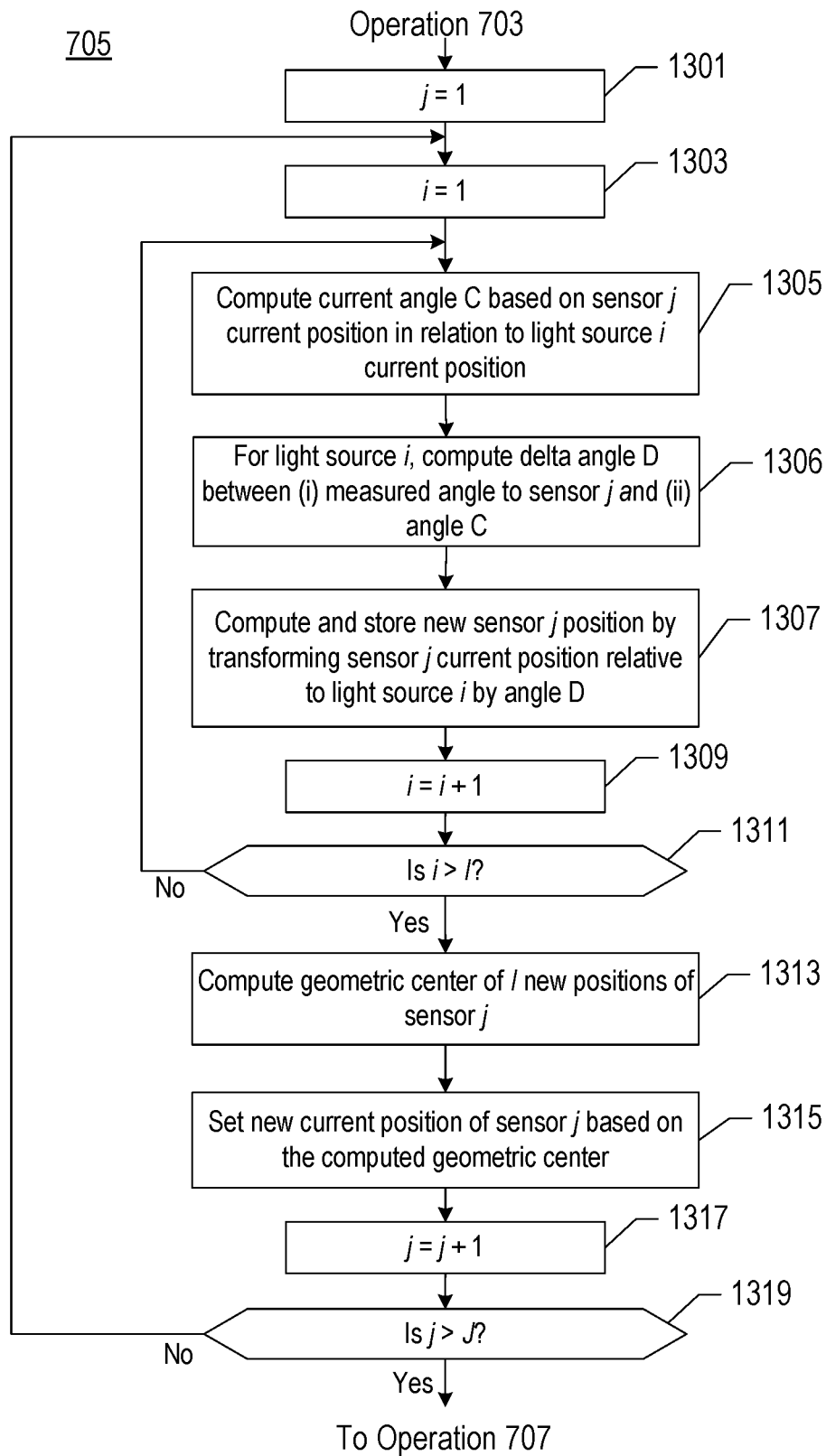


Figure 13



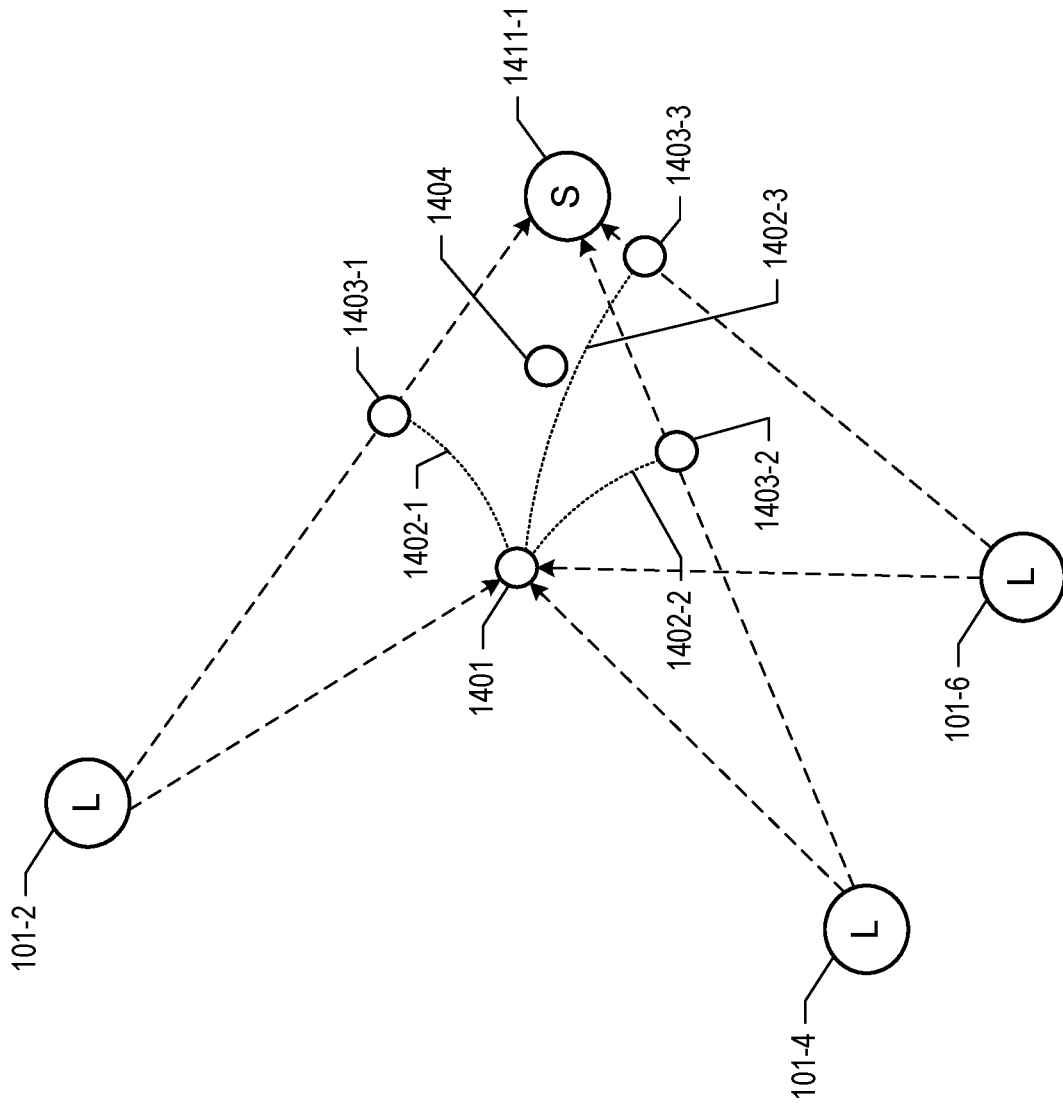


Figure 14

Figure 15

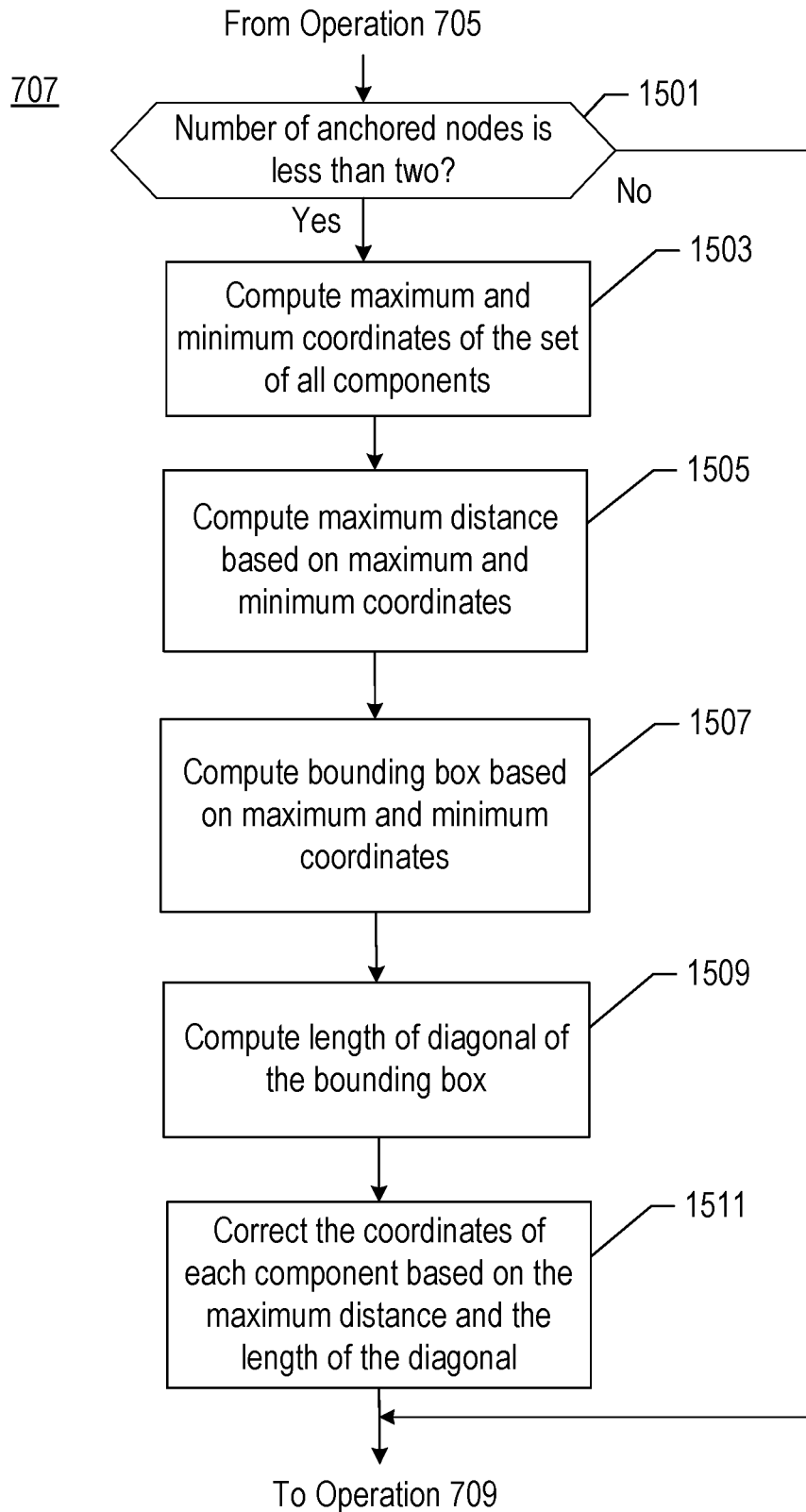
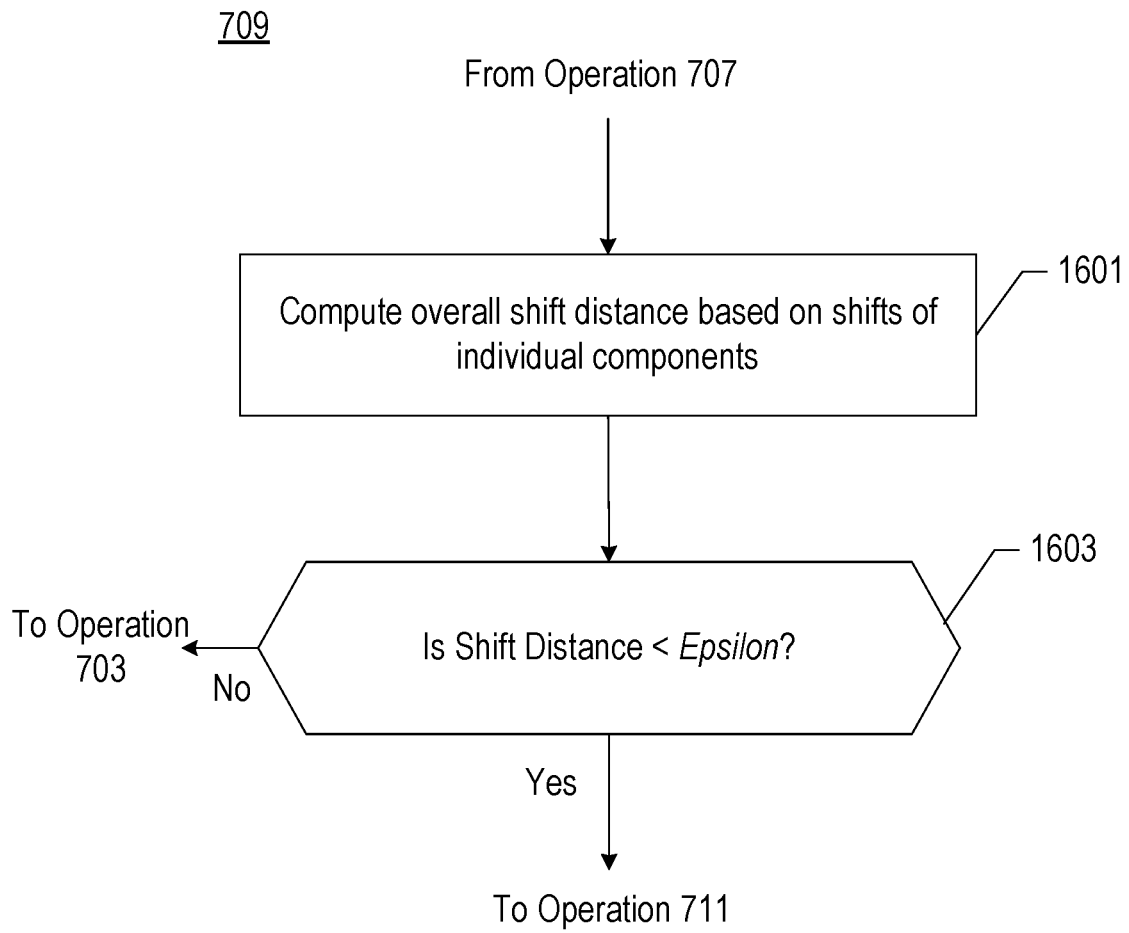


Figure 16



**SYSTEM AND METHOD FOR
DISCOVERING THE TOPOLOGY OF
DEVICES WITHIN A BUILDING
AUTOMATION AND CONTROL SYSTEM**

CROSS REFERENCE TO RELATED
APPLICATIONS

This application is related to “Configurable Light Sensor Comprising a Photocell Array,” U.S. application Ser. No. 16/168,755, filed on the same day as the present application and incorporated by reference herein.

FIELD OF THE INVENTION

The present invention relates to building automation and control in general, and, more particularly, to discovering the topology of devices within a building automation and control system, including the measuring of the angular position of one or more of the devices.

BACKGROUND OF THE INVENTION

“Commercial building automation,” or “commercial automation,” refers to the use of computer and information technology to control commercial building systems, such as lighting, HVAC, audio-visual, smoke detection, security, and shading, among others. Using specialized hardware and control logic, building devices can monitor their environment and can be controlled automatically. Although commercial automation has been available at some level of sophistication for some time, it steadily becomes more practical, both from a technological and cost perspective.

Lighting automation, in particular, has evolved over time. Lighting systems now exist in which luminaires that comprise control logic and controllable lamps are networked together, in what is sometimes referred to as “connected lighting” or networked “smart lighting.” In such a network of “smart nodes,” the sensors that are associated with the luminaires collect data about the local environment, such as data related to occupancy and data related to ambient lighting in the vicinity of the luminaires. The networked sensors and luminaires communicate with one other and adjust the light output of the lamps via the control logic, in some cases based on the sensor data.

There can be a large number of such connected devices within a building, in the hundreds, or even thousands, of devices sharing data with one another. Consequently, there are various issues to consider in planning and implementing a system of connected devices, so that the devices are installed and operate in a coordinated way. For example, it is important for an engineer who is commissioning a connected lighting system to have knowledge of the connected system’s topology, which includes having knowledge of the way in which the constituent devices are interrelated or arranged, and of where each device is within a building, within a room within the building, and in relation to one or more other devices within the connected system. Understanding the layout of light sources and sensors is important for various applications, including configuring daylight harvesting scenarios, organizing the light sources in groups, defining scenes, and performing maintenance. However, discovering the connected system’s topology manually can be labor-intensive and, consequently, can be costly, in some cases prohibitively costly.

Thus, what is needed is a technique for discovering the topology of a connected system, without at least some of the disadvantages and costs in the prior art.

SUMMARY OF THE INVENTION

The present invention relates to a light sensor that comprises a matrix of photocells, wherein the light sensor is a node within a connected lighting system and under the control of a configuring device. The configuring device coordinates the discovery of the topology of the connected lighting system, as described below. The light sensor of the illustrative embodiment measures ambient light provided by a light source and reflected from a surface in an area to be monitored, wherein the light source can be another node within the connected lighting system. A microcontroller in the light sensor reads each individual photocell and processes the signals from the photocells according to one or more of the methods disclosed herein, in order to compute and report an angle of the location of a light source in the connected lighting system. The configuring device uses the computed angle as part of the topology discovery process. Subsequently, the sensor node can monitor an area and report sensor output values based on measurements made from the photocells.

In accordance with the illustrative embodiment, and while under the control of a configuring device within the connected lighting system, the light sensor computes the angle of the location of the light source, which is the angular position of the light source in relation to the light sensor, through two stages of measurement. In a first stage of measurement, the sensor measures the background in the area served by the connected lighting system. For example, the measurement occurs when all of the light sources in the area are turned on and emitting light. In a second stage of measurement, which can occur either after or before the first stage, the sensor measures the light after the output of the particular light source is changed, typically after the light source is turned off. The angular position of the light source is determined based on one or more differences between the first and second stages of measurement, as disclosed herein. The light sensor then reports the value of the angular position to the configuring device, which can present the information to a user, store the information for future use, and/or transmit the information to another data-processing system.

In accordance with the illustrative embodiment, the configuring device discovers the topology of the connected lighting system, first by generating a data set that includes the angular positions of one or more light sources and obtained from one or more sensor nodes, and then by iteratively computing the spatial position, relative or absolute, of each non-anchored component in the lighting system that is, of each component for which the location of the component is unknown prior to the iterative process. In particular, each iteration of the processing includes computing the spatial position of each non-anchored light source, computing the spatial position of each non-anchored sensor node, scaling the distances among the components, as needed, and performing a convergence check in order to determine whether the topology discovery process has progressed sufficiently.

By performing the discovery process automatically, the configuring device of the illustrative embodiment, in concert with the light sensors computing angular positions, reduces

or eliminates the need for an engineering technician to perform the discovery process manually, thereby saving time and money.

A first illustrative node comprising: a photocell matrix comprising at least three photocells configured to sense light levels and to provide a plurality of illuminance signals that represent the light levels, wherein the at least three photocells are arranged such that at least two photocells are along each of a first dimension and a second dimension of the photocell matrix; a controller configured to: i) measure light levels sensed by the at least three photocells at a first time and in response to the first node receiving a first input signal, resulting in a plurality of first measurements, wherein the controller makes the first measurements from illuminance signals received via a first signal path and that represent the light levels sensed by the at least three photocells at the first time, ii) measure light levels sensed by the at least three photocells at a second time, resulting in a plurality of second measurements, wherein the controller makes the second measurements from illuminance signals received via the first signal path and that represent the light levels sensed by the at least three photocells at the second time, and wherein the first and second times are different from each other, and iii) compute a first angle across the first and second dimensions based on a first difference between at least one of the first measurements and at least one of the second measurements; and a communication interface configured to: i) receive the first input signal, and ii) transmit a first output signal that represents the first angle.

A first illustrative method comprising: receiving a first signal; measuring light levels sensed by at least three photocells in a photocell matrix at a first time and in response to receiving the first signal, resulting in a plurality of first measurements, wherein the first measurements are made from illuminance signals that represent the light levels sensed by the at least three photocells at the first time, and wherein the at least three photocells are arranged such that at least two photocells are along each of a first dimension and a second dimension of the photocell matrix; measuring light levels sensed by the at least three photocells in the photocell matrix at a second time, resulting in a plurality of second measurements, wherein the second measurements are made from illuminance signals that represent the light levels sensed by the at least three photocells at the second time, and wherein the first and second times are different from each other; computing a first angle across the first and second dimensions from a first difference between at least one of the first measurements and at least one of the second measurements; and transmitting a first output signal that represents the first angle.

A second illustrative method comprising: receiving, by the data-processing system, a first measurement of the first light source in relation to a first sensor, wherein the first measurement is received from the first sensor; receiving, by the data-processing system, a second measurement of the first light source in relation to a second sensor, wherein the second measurement is received from the second sensor; generating a first estimate of the position of the first light source, based on a first angle at the first sensor between (i) a first direction toward a current light source position and (ii) a second direction that is defined by the first measurement; generating a second estimate of the position of the first light source, based on a second angle at the second sensor between (i) a third direction toward the current light source position and (ii) a fourth direction that is defined by the second measurement; generating an updated light source position of the first light source based on the first estimate

and the second estimate; and presenting the updated light source position of the first light source to a user.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a floor plan of building **100** in accordance with the illustrative embodiment of the present invention, within which smart nodes are physically situated.

FIG. 2 depicts connected lighting network **200** in accordance with the illustrative embodiment.

FIG. 3 depicts the salient components of wireless device **111** according to the illustrative embodiment.

FIG. 4 depicts the salient components of smart node **101-m** according to the illustrative embodiment.

FIG. 5 depicts the salient components of sensor node **101-1** according to the illustrative embodiment.

FIG. 6 depicts optical system **532** and photocell matrix **533** of sensor node **101-1**.

FIG. 7 depicts salient operations of method **700** according to the illustrative embodiment, by which wireless device **111** performs various functions that are related to discovering the topology of connected network **200**.

FIGS. **8A** and **8B** provide a graphical overview of the operations depicted in FIG. 7.

FIGS. **9A** and **9B** depict salient operations of method **701**, by which wireless device **111** generates a dataset of input data to be used in the discovery process.

FIG. **10** depicts salient operations of method **1000**, by which sensor node **101-1** measures and provides an angular position of a light source in relation to the sensor node.

FIG. **11** depicts salient operations of method **703**, by which wireless device **111** computes the spatial position of each non-anchored light source.

FIG. **12** provides a graphical depiction of at least some of the operations in FIG. **11**.

FIG. **13** depicts salient operations of method **705**, by which wireless device **111** computes the spatial position of each non-anchored sensor node.

FIG. **14** provides a graphical depiction of at least some of the operations in FIG. **13**.

FIG. **15** depicts salient operations of method **707**, by which wireless device **111** scales the distances between the components.

FIG. **16** depicts salient operations of method **709**, by which wireless device **111** performs a convergence check to determine whether or not the discovery process has converged.

DETAILED DESCRIPTION

Based on—For the purposes of this specification, the phrase “based on” is defined as “being dependent on” in contrast to “being independent of”. The value of Y is dependent on the value of X when the value of Y is different for two or more values of X. The value of Y is independent of the value of X when the value of Y is the same for all values of X. Being “based on” includes both functions and relations.

Control—For the purposes of this specification, the infinitive “to control” and its inflected forms (e.g., “controlling”, “controlled”, etc.) should be given the ordinary and customary meaning that the terms would have to a person of ordinary skill in the art at the time of the invention.

Controller—For the purposes of this specification, the term “controller” is defined as hardware or hardware and

software that perform mathematical and/or logical operations and that control other devices based, at least in part, on the operations performed.

Generate—For the purposes of this specification, the infinitive “to generate” and its inflected forms (e.g., “generating”, “generated”, etc.) should be given the ordinary and customary meaning that the terms would have to a person of ordinary skill in the art at the time of the invention.

Lamp—For the purposes of this specification, the term “lamp” is defined as a device for providing illumination, comprising an electric bulb and its holder.

Luminaire—For the purposes of this specification, the term “luminaire, or “luminaire node,” is defined as a lighting unit comprising a lamp and a controller for controlling the lamp.

Light source—For the purposes of this specification, the term “light source” is defined as being either a luminaire, which comprises a lamp, or the lamp itself, which can be part of either a luminaire node or a different type of connected node (e.g., a sensor node, etc.).

Measure—For the purposes of this specification, the infinitive “to measure” and its inflected forms (e.g., “measuring”, “measured”, etc.) should be given the ordinary and customary meaning that the terms would have to a person of ordinary skill in the art at the time of the invention.

Photocell—For the purposes of this specification, the term “photocell,” or “photoelectric cell,” is defined as a device that generates an electric current or voltage dependent on the degree of illumination.

Position—For the purposes of this specification, the term “position,” is defined as a place where someone or something is located or has been put.

Receive—For the purposes of this specification, the infinitive “to receive” and its inflected forms (e.g., “receiving”, “received”, etc.) should be given the ordinary and customary meaning that the terms would have to a person of ordinary skill in the art at the time of the invention.

Sensor node—For the purposes of this specification, the term “sensor node” is defined as a unit comprising one or more sensors for detecting one or more physical conditions and a controller for responding to information received from the one or more sensors.

Transmit—For the purposes of this specification, the infinitive “to transmit” and its inflected forms (e.g., “transmitting”, “transmitted”, etc.) should be given the ordinary and customary meaning that the terms would have to a person of ordinary skill in the art at the time of the invention.

To facilitate explanation and understanding of the present invention, the following description sets forth several details. However, it will be clear to those having ordinary skill in the art, after reading the present disclosure, that the present invention may be practiced without these specific details, or with an equivalent solution or configuration. Furthermore, some structures, devices, and operations that are well known in the art are depicted in block diagram form in the accompanying figures in order to keep salient aspects of the present invention from being unnecessarily obscured.

FIG. 1 illustrates a floor plan of building 100 in accordance with the illustrative embodiment of the present invention, within which smart nodes are physically situated according to the floor plan. Building 100 is equipped with smart nodes 101-1 through 101-M, wherein M is a positive integer (e.g., M equal to 17 as depicted, etc.). As depicted in FIG. 1, nodes 101-1, 101-3, 101-5, 101-7, 101-9, 101-13, 101-15, and 101-17 are light sensors (denoted by “S” in the figure). Nodes 101-2, 101-4, 101-6, 101-8, 101-10, 101-11, 101-12, 101-14, and 101-16 are light fixtures, or “lumi-

nares,” (denoted by “L”). In some embodiments of the present invention, the light sensors are specifically ambient light sensors. Wireless device 111 (denoted by “P”) is also present within building 100. The networked nodes communicate wirelessly with one another via transmitted signals within a data network. In some alternative embodiments of the present invention, however, one or more of the depicted elements can communicate via wired connections.

The connected lighting system in FIG. 1 includes 17 smart nodes configured with one smartphone, with eight light sensors and nine luminaires. As those who are skilled in the art will appreciate, after reading this specification, various embodiments of the present invention can include a different total number of nodes and/or different numbers than depicted of the individual types of nodes.

Wireless device 111, a type of data-processing system, is a wireless telecommunications terminal that is configured to transmit and/or receive communications wirelessly. It is an apparatus that comprises memory, processing components, telecommunication components, and user interface components (e.g., display, speaker, keyboard, microphone, etc.). Wireless device 111 comprises the hardware and software necessary to be compliant with the protocol standards used in the wireless networks in which it operates and to perform the processes described below and in the accompanying figures. For example and without limitation, wireless device 111 is capable of:

- i. handling an incoming or outgoing telephone call or other communication (e.g., application-specific data, SMS text, email, media stream, etc.),
- ii. provisioning one more devices into network nodes 101-1 through 101-M, and
- iv. Configuring one or more of network nodes 101-1 through 101-M.

Wireless device 111 is described in detail below and in FIG. 3.

Wireless device 111 is illustratively a smartphone with at least packet data capability provided and supported by one or more networks in which it operates, including data network 200 in FIG. 2. Device 111 is configured to execute a software application (e.g., an “app”) for configuring one or more of the smart devices (e.g., lights, sensors, etc.) the data network. In particular, the application enables the configuring of one or more of the sensor nodes (e.g., by an installing technician, etc.).

In some embodiments of the present invention, device 111 is a different type of data-processing system, or executes an application that is different than a device-based app, or both. For example and without limitation, wireless device 111 can be referred to by a variety of alternative names such as, while not being limited to, a mobile station, a wireless transmit/receive unit (WTRU), a user equipment (UE), a wireless terminal, a cell phone, or a fixed or mobile subscriber unit. Wireless device 111 can be any other type of device (e.g., a tablet, etc.) that is capable of operating in a wireless network environment, mobility-oriented or otherwise.

In some embodiments of the present invention, device 111 comprises, or is itself, an Ethernet-to-Bluetooth gateway. In such embodiments, device 111 is wireless in the sense that it has and it uses a Bluetooth radio on one end of its gateway function, while the other end of the gateway function can interface to Ethernet cable (i.e., a wired interface). In some other embodiments, device 111 can be a different type of dedicated gateway.

Each smart node 101-m in FIG. 1, wherein m has a value between 1 and M, inclusive, is an apparatus that comprises

memory, processing components, and communication components. Node **101-m** is configured to transmit signals **102-m** that convey control-related information, such as packet-based messages. Luminaire **101-m** (i.e., nodes **101-2**, **101-4**, **101-6**, etc.) is also configured to provide light at an output that is based, at least in part, on the content of one or more messages received from one or more other nodes. Sensor node **101-m** (i.e., nodes **101-1**, **101-3**, **101-5**, etc.) is also configured to sense one or more physical conditions, such as light, and can transmit messages based on the one or more physical conditions sensed. Node **101-m** is described in detail below and in FIG. 4.

In accordance with the illustrative embodiment, nodes **101-1** through **101-17** constitute an automation and control system in a commercial building, such as an office space or a retail space. As those who are skilled in the art will appreciate after reading this specification, however, the system disclosed herein can also be applied to a different type of building, such as a home, or to include the environment surrounding the building, or to any environment in which automated control can be applied.

Furthermore, the building in which the nodes are situated can be any type of structure with a roof and walls, or can instead be a defined area that comprises multiple sub-areas (e.g., open space, one or more conference rooms, one or more corridors, one or more closed offices, etc.). At least a portion of the area and/or sub-areas can be defined by something other than a roof and/or walls (e.g., a tent, an outdoor pavilion, a covered parking lot, a stadium or arena, etc.).

As those who are skilled in the art will appreciate after reading this specification, the nodes can be positioned in any geometry or geometries with respect to one another, provided that each node is within communication range of one or more of the other nodes.

In accordance with the illustrative embodiment, nodes **101-1** through **101-M** constitute a connected lighting system. As those who are skilled in the art will appreciate after reading this specification, however, the system disclosed herein can also be applied to control a different type of domain than lighting. In other words, any reference herein to lighting system, light level, a light source, illuminance, a light sensor (e.g., photocell array or matrix, photocell, etc.), and any other lighting-related term, can be replaced with the corresponding term or terms related to a domain different than lighting.

For example and without limitation, a light sensor node and a luminaire node can be replaced respectively with a temperature sensor node and a heating and/or cooling unit in the climate control domain. In the foregoing example, terms corresponding to the list in the preceding paragraph can be temperature, a heating/cooling source, heat, a heat sensor (e.g., infrared sensor, etc.), respectively, although other equivalent terms can be used instead. As another non-limiting example, a light sensor node and a luminaire node can be replaced respectively with a sound/vibration sensor node and a loudspeaker in the sound or audio domain. In the foregoing example, terms corresponding to the list in the preceding paragraph can be sound level, a sound source (e.g., loudspeaker, etc.), sound, a sound sensor (e.g., microphone, etc.), respectively, although other equivalent terms can be used instead.

FIG. 2 depicts connected lighting network **200** in accordance with the illustrative embodiment. Network **200** comprises smart nodes **101-1** through **101-M** and wireless device **111** from FIG. 1. For purposes of clarity, only light-sensor nodes **101-1**, **101-3**, and **101-5** and luminaire nodes **101-2**,

101-4, and **101-6** are depicted in FIG. 2. The depicted nodes communicate wirelessly with one another via transmitted signals **102-1**, **102-2**, **102-3**, **102-4**, **102-5**, **102-6**, and **112**.

Network **200** is a mesh data network that enables communication between wireless device **111** and smart nodes **101-1** through **101-M**. To this end, the nodes within network **200** distribute data (e.g., the packet-based messages, etc.) in accordance with Bluetooth mesh networking. A “mesh network” is a network topology in which each node relays data for the network. The nodes that are involved cooperate in the distribution of data in the network. A mesh network can relay messages using either a flooding technique or a routing technique.

In some other embodiments, network **200** communicates via one or more other radio telecommunications protocols other than or in addition to Bluetooth mesh networking such as, but not limited to, Z-Wave, ZigBee, Thread, Wi-Fi, straight Bluetooth Low Energy (BLE), classic Bluetooth, and so on. Furthermore, as those who are skilled in the art will appreciate after reading this specification, wireless device **111** and at least some smart nodes **101-1** through **101-M** in some embodiments can be connected directly and non-wirelessly to one other, at least for some purposes and/or for some portion of time, such as through Universal Serial Bus (USB), FireWire™, or Thunderbolt™, for example and without limitation.

FIG. 3 depicts the salient components of wireless device **111** according to the illustrative embodiment. Wireless device **111** is also referred to as the “configuring node.” Wireless device **111** is based on a data-processing apparatus whose hardware platform comprises: controller **303**, memory **304**, and communication interface **305**, interconnected as shown.

Controller **303** is a processing device, such as a microcontroller or microprocessor with a controller interface, which are well known in the art. Controller **303** is configured such that, when operating in conjunction with the other components of wireless device **111**, controller **303** executes software, processes data, and telecommunicates according to the operations described herein.

Memory **304** is non-transitory and non-volatile computer storage memory technology that is well known in the art (e.g., flash memory, etc.). Memory **304** is configured to store an operating system, application software, and a database. The operating system is a collection of software that manages, in well-known fashion, wireless device **111**’s hardware resources and provides common services for computer programs, such as those that constitute the application software. The application software that is executed by controller **303** according to the illustrative embodiment enables wireless device **111** to perform the functions disclosed herein.

It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one memory **304**; or comprise subdivided segments of memory **304**; or comprise a plurality of memory technologies that collectively store the operating system, application software, and database.

Communication interface **305** is configured to enable wireless device **111** to telecommunicate with other devices, by receiving signals therefrom and/or transmitting signals thereto via receiver **321** and transmitter **322**, respectively. In order to communicate with devices outside of mesh network **200**, communication interface **305** communicates in accordance with WiFi or other applicable standard. In order to communicate with other devices within mesh network **200**, module **305** communicates in accordance with Bluetooth mesh networking. In some other embodiments, communi-

cation interface **305** communicates via one or more other radio telecommunications protocols other than or in addition to WiFi and Bluetooth mesh networking, such as, but not limited to, a cellular network standard (e.g., LTE, GSM, etc.), Z-Wave, ZigBee, Thread, Wi-Fi, straight Bluetooth

Low Energy (BLE), classic Bluetooth, and so on. Receiver **321** is a component that enables wireless device **111** to telecommunicate with other components and systems by receiving signals that convey information therefrom and through antenna **323**. It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one receiver **321**.

Transmitter **322** is a component that enables wireless device **111** to telecommunicate with other components and systems by transmitting signals that convey information thereto and through antenna **324**. It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one transmitter **322**.

In accordance with the illustrative embodiment, wireless device **111** uses communication interface **305** in order to telecommunicate wirelessly with external devices. It will be clear to those skilled in the art, however, after reading the present disclosure, how to make use and use various embodiments of the present invention in which wireless device **111** communicates via a wired protocol (e.g., X10, KNX, etc.) over physical media (e.g., cable, wire, etc.) with one or more external devices, either in addition to or instead of the wireless capability provided by communication interface **305**.

In some embodiments of the present invention, wireless device **111** is responsible for initiating the configuration process, by transmitting a command to one or more sensor nodes, including sensor node **101-1**, wherein the command is for configuring the sensor node. The sensor node receives and acts upon the command as described below and in regard to FIG. 7.

FIG. 4 depicts the salient components of smart node **101-m** according to the illustrative embodiment. Node **101-m** is based on a data-processing apparatus whose hardware platform comprises at least some of: sensor unit **401-1** through **401-H**, wherein H is a positive integer, actor unit **402-1** through **402-K**, wherein K is a positive integer, controller **403**, memory **404**, and communication interface **405**, interconnected as shown.

Various nodes within mesh network **200** can comprise different combinations of sensors, actors, controllers, memory, and communications modules. Each luminaire node in FIG. 2, for example, includes a controllable lamp (i.e., an actor unit), a controller, and, optionally, a sensor unit (e.g., ambient light sensor, occupancy sensor, etc.), although some luminaires might not include a sensor unit. Each sensor node in FIG. 2, for example includes a sensor unit and a controller, but not necessarily an actor unit (e.g., lamp, etc.). An illustrative configuration of sensor node **101-1** is described below and in regard to FIG. 5. As those who are skilled in the art will appreciate after reading this specification, different configurations of mesh nodes are possible, wherein each node is based on one or more of the components that are described below.

Sensor unit **401-h**, wherein h has a value between 1 and H, inclusive, is an apparatus that comprises memory, processing components, and communication components, and is configured to gather information about the environment that is accessible by the sensor unit. Each sensor is configured to monitor a particular physical condition in well-known fashion (e.g., temperature, ambient light, humidity,

occupancy, etc.). For example, sensor nodes **101-1**, **101-3**, and **101-5** comprise an ambient light sensor.

Each sensor unit is configured to report a state of the condition by providing input signals to controller **403**, wherein the values of the input signals are representative of the states being reported. A given sensor unit **401-h** can report discrete input signal values and/or a continuum of states and can report states at particular times and/or continuously. A change in state, which is determined by controller **403** as described below, can occur based one or more sensor units detecting changes in the following, in any combination:

- i. environmental probes (e.g., temperature, ambient light, motion, infrared signature, humidity, etc.).
- ii. electrical inputs (i.e., binary, analog, bus), including from a switch.
- iii. signals received via radio (e.g., proximity beacons, etc.).
- iv. a state of the internal logic, woken up periodically based on time or on an external event.

For example and without limitation, a state change can correspond to a switch being actuated, occupancy being detected, a timer or counter reaching a predefined value, and so on.

Actor unit **402-k**, wherein k has a value between 1 and K, inclusive, is an apparatus that comprises memory, processing components, and communication components, and is capable of doing something in the course of being affected by signals originating externally to the actor component, such as from controller **403**, as described in detail below. Each actor unit acts upon its environment in well-known fashion.

Actor unit **402-k** is configured to receive, transmit, process, and/or relay signals conveying data, as well as being configured to affect a condition, physical or otherwise, in its environment, for example by generating a control signal. In accordance with the illustrative embodiment, actor unit **402-1** of each luminaire node **101-2**, **101-4**, and **101-6** is a lamp whose output is modifiable by controller logic executed by controller **403**.

As those who are skilled in the art will appreciate after reading this disclosure, actor unit **402-k** can provide a different function than controlling a lamp to give light according to a configurable light output. For example and without limitation, the condition being affected can be:

- i. lighting, which can be adjusted (e.g., turning on or off, changing light output, changing brightness, changing color or mood, changing illuminance, displaying a picture or pattern, etc.).
- ii. sound, which can be adjusted (e.g., increasing or decreasing volume, changing playlist or mood, turning on/off, selecting signal source, etc.).
- iii. room climate, which can be controlled (e.g., increasing or decreasing temperature, humidity, air fragrance, fan speed, etc.).
- iv. an alert, which can be generated (e.g., of an email, of an SMS message, etc.).
- v. monitoring by a camera, which can be panned or tilted.
- vi. office meeting/presentation settings (e.g., selecting one or more of signal source, streaming application, multimedia to play, audio language, subtitles, chapter, play/pause/stop, rewind/fast forward, etc.).
- vii. connected/smart video monitor features (e.g., selecting application to be launched, navigating through on-screen menus, etc.).

- viii. virtual keyboard navigation on virtual keyboard displayed by other device (e.g., video monitor, set-top box, etc.).
- ix. control of shades/window coverings/blinds.
- x. access control (e.g., unlocking/locking doors, opening/shutting doors, authorizing access to selected rooms or zones, etc.).

Furthermore, node **101-m** can comprise any combination of and any number of actor functions. As those who are skilled in the art will appreciate, after reading this disclosure, node **101-m** that comprises one or more actor functions can be in a variety of forms, such as a luminaire in a lighting system, a media player as part of an audio/video system, a heater and/or ceiling fan as part of an environment control system, an outgoing-email server as part of a messaging system, an actor in a water sprinkler system, a pump, a robot or robotic arm, a pan/tilt camera, a switch, a motor, a servo mechanism, and so on.

Controller **403** is a processing device, such as a microcontroller or microprocessor with a controller interface, which are well known in the art. For example and without limitation, the microcontroller can be part of an nRF52832 integrated circuit (IC) by Nordic Semiconductor, which is integrated with Bluetooth, or can be a SAM3X IC by Atmel Corporation. Controller **403** is configured such that, when operating in conjunction with the other components of node **101-1**, controller **403** executes software, processes data, and telecommunicates according to the operations described herein, including those depicted in FIG. **10** which pertain to computing the angle of the location of a light source based on measuring light reflected by a surface illuminated by the light source.

Memory **404** is non-transitory and non-volatile computer storage memory technology that is well known in the art (e.g., flash memory, etc.). Memory **404** is configured to store an operating system, application software, and a database. The operating system is a collection of software that manages, in well-known fashion, node **101-1**'s hardware resources and provides common services for computer programs, such as those that constitute the application software. The application software that is executed by controller **403** according to the illustrative embodiment enables node **101-1** to perform the functions disclosed herein.

It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one memory **404**; or comprise subdivided segments of memory **404**; or comprise a plurality of memory technologies that collectively store the operating system, application software, and database.

Communication interface **405** is configured to enable node **101-m** to telecommunicate with other devices and systems, including other mesh network nodes, by receiving signals therefrom and/or transmitting signals thereto via receiver **421** and transmitter **422**, respectively. Communication interface **405** communicates in accordance with Bluetooth mesh networking. In some other embodiments, communication interface **405** communicates via one or more other radio telecommunications protocols other than or in addition to Bluetooth mesh networking such as, but not limited to, Z-Wave, ZigBee, Thread, Wi-Fi, straight Bluetooth Low Energy (BLE), classic Bluetooth, and so on.

Receiver **421** is a component that enables node **101-m** to telecommunicate with other components and systems by receiving signals that convey information therefrom and through antenna **423**. It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one receiver **421**.

Transmitter **422** is a component that enables node **101-m** to telecommunicate with other components and systems by transmitting signals that convey information thereto and through antenna **424**. For example and without limitation, transmitter **422** is configured to transmit packets comprising the information described below and in FIGS. **6** through **10**. It will be clear to those having ordinary skill in the art how to make and use alternative embodiments that comprise more than one transmitter **422**.

In accordance with the illustrative embodiment, node **101-m** uses communication interface **405** in order to telecommunicate wirelessly with external devices. It will be clear to those skilled in the art, however, after reading the present disclosure, how to make use and use various embodiments of the present invention in which node **101-m** communicates via a wired protocol (e.g., X10, KNX, etc.) over physical media (e.g., cable, wire, etc.) with one or more external devices, either in addition to or instead of the wireless capability provided by communication interface **405**. In some embodiments of the present invention, communication interface **405** is implemented on hardware that is physically distinct from that of controller **403**, while in some other embodiments communication interface **405** is implemented on the same hardware (IC) as controller **403**.

In generating and transmitting one or more packets that convey a message within mesh network **200**, along with including its own network address as the source address in the message, node **101-m** is said to originate the message. As described below, node **101-m** is further capable of forwarding a message that has been originated by a different node.

FIG. **5** depicts the salient components of sensor node **101-1** according to the illustrative embodiment. Sensor node **101-1** comprises: sensor unit **401-1**, controller **403**, memory **404**, communication interface **405**, and housing **506**, inter-related as shown. The foregoing components of sensor node **101-1** are described above and in regard to FIG. **4**, and details specific to sensor node **101-1** are provided below.

Sensor unit **401-1** is an apparatus that comprises memory, processing components, and communication components, and is configured to gather information about the environment that is accessible by the sensor unit. Sensor unit **401-1** is configured to monitor a particular physical condition in well-known fashion in this case, light reflected off of viewable area **531**. To this end, sensor unit **401-1** comprises lens **532** and photocell matrix **533**. Lens **532** directs light rays **540** from viewable area **531** onto photocell matrix **533**, which comprises P photocells, wherein P is a positive integer that is greater than one. The P photocells of matrix **533** provide illuminance signals, in the form of electrical signals, to controller **403** along respective signal paths **542-1** through **542-P**, wherein the values or levels of the illuminance signals are representative of the light levels sensed by the photocells. Lens **532** and photocell matrix **533** are described below and in regard to FIG. **6**.

Communication interface **405** is configured to enable node **101-1** to telecommunicate with other devices and systems, including other mesh network nodes, by receiving signals therefrom and/or transmitting signals thereto via receiver **421** and transmitter **422**, respectively, an exchanging the signals with controller **403** via signal path **543**.

Housing **506** contains sensor unit **401-1**, controller **403**, memory **404**, and communication interface **405**. It will be clear to those having ordinary skill in the art how to make and use housing **506**.

FIG. **6** depicts optical system **532** and photocell matrix **533**, which are included in sensor unit **401-1**. Optical system **532**, comprising a lens, directs light from viewable area **531**

onto photocell matrix **533**. In some embodiments of the present invention, optical system **532** is configured to direct the light so that the image from an imaged object **611** within viewable area **531** is out of focus on photocell matrix **533**. In other words, optical system **532** acts as a low-pass filter on the image, having the effect of removing at least some high-frequency components of the image.

In some alternative embodiments of the present invention, optical system **532** utilizes something other than, or in addition to, a lens to direct the reflected light onto the photocell, such as an aperture or a focusing mirror.

Photocell matrix **533** is depicted as a two-dimensional matrix having photocells **601-1** through **601-P**, wherein P has a value equal to 9 as depicted and wherein the photocells are situated in three rows and three columns in the matrix. Multiple photocells in matrix **533** are collectively referred to in this specification as “photocells **601**.” As those who are skilled in the art will appreciate after reading this specification, P can have a value different than 9 in some alternative embodiments of the present invention. Furthermore, the dimensioning of the matrix (i.e., number of rows and columns) can be different than depicted. The P photocells of photocell matrix **533** provide illuminance signals to controller **403** as depicted in FIG. **4**.

The photocells of matrix **533** can be implemented with phototransistors, photoresistors, or an integrated chip, for example and without limitation. The photocell matrix can come as a prefabricated component, such as the OV9281 or OV9282 image sensors by OmniVision Technologies Inc., or can be created from discrete components as the TEMT6200FX01 phototransistor by Vishay Technology, Inc. or the LV0104CS photo IC by ON Semiconductor.

Viewable area **531** as depicted is the total area of one or more surfaces from which light (e.g., reflected light, etc.) is being directed by lens **532** to within the boundaries of photocell matrix **533**. At least some of the x-y coordinate points within viewable area **531** map to corresponding x-y points within photocell matrix **533**. For example, imaged object **611** might be sensed by one or more of photocells **601-4**, **601-5**, **601-7**, and **601-8** as depicted, as a result of how lens **532** directs the viewable image onto the photocell matrix.

Operations of Device **111** in Discovering the Topology of Connected Network **200**: FIG. **7** depicts salient operations of method **700** according to the illustrative embodiment, by which wireless device **111** performs various functions that are related to discovering the topology of connected network **200**, including the sensor nodes and luminaire nodes. For pedagogical purposes, method **700** is described in terms of discovering the topology of the three sensor nodes and the three luminaire nodes depicted in FIG. **2**. It will clear to those skilled in the art, however, after reading this specification, how to extend the methods disclosed herein to any number of nodes and to any combination of the different types of nodes.

An overview of the operations disclosed herein is provided in FIGS. **8A** and **8B**. Wireless device **111** obtains the angular positions of the light sources with respect to the sensors, wherein the angular position is oriented within the x-y plane of viewable area **531** of FIG. **6**. The angular positions of the light sources are illustrated in FIG. **8A**, which shows three sensors **101-1**, **101-3**, and **101-5** and three light sources **101-2**, **101-4**, and **101-6** at their initial assumed locations. The three sensors are assumed to share the same location (i.e., at “**101-S**”), and the three light sources are assumed to share the same location (i.e., at “**101-L**”).

FIGS. **8A** and **8B** also shows the angular positions, which are depicted as vectors, of various nodes with respect to other nodes. Angular positions **801-1-1**, **801-1-2**, and **801-1-3** correspond to the angular positions of respective light sources **101-2**, **101-4**, and **101-6** with respect to sensor **101-1**. Angular positions **801-2-1**, **801-2-2**, and **801-2-3** correspond to the angular positions of respective light sources **101-2**, **101-4**, and **101-6** with respect to sensor **101-3**. And angular positions **801-3-1**, **801-3-2**, and **801-3-3** correspond to the angular positions of respective light sources **101-2**, **101-4**, and **101-6** with respect to sensor **101-5**. For purposes of clarity, the vectors toward the various sensors with respect to light sources **101-2**, **101-4**, and **101-6** are not shown. It will, however, be clear to those who are skilled in the art, after reading this specification, how to determine angular positions of the sensors with respect to the light sources.

Optionally, device **111** also obtains the location of selected light sources and sensors and/or the distances between selected light sources and sensors. The processing allows for inconsistent input data due to measurement errors of angles and distances.

In a number of iterations, wireless device **111** computes the locations of the light sources and the sensors. Device **111** stops the iterations if the accumulated shift in an iteration is below a threshold. The final computed locations of the sensors and light sources is illustrated in FIG. **8B**, reflecting the physical positions of the same sensors and light sources depicted in FIG. **1** in building **100**. FIG. **8B** also shows the same angular positions that are depicted in FIG. **8A** and remain consistent throughout the discovery process.

In regard to method **700**, as well as to the other methods depicted in the flowcharts and message flow diagrams contained herein, it will be clear to those having ordinary skill in the art, after reading the present disclosure, how to make and use alternative embodiments of the disclosed methods in which the recited operations, sub-operations, and messages are differently sequenced, grouped, or sub-divided all within the scope of the present invention. It will be further clear to those skilled in the art, after reading the present disclosure, how to make and use alternative embodiments of the disclosed methods wherein some of the described operations, sub-operations, and messages are optional, are omitted, or are performed by other elements and/or systems than the illustrative devices associated with the respective methods.

Furthermore, the indexing (i.e., “i”, “j”) that appears in the processing flowcharts herein is used in order to simplify the explanation of some of the processing that concurrently involves sensor nodes and light sources. The indexing is used instead of explicitly referring to each node by its reference numeral (e.g., “sensor node **101-1**,” “light source **101-2**,” etc.). For example, sensor nodes **1**, **2**, and **3** correspond to sensor nodes **101-1**, **101-3**, and **101-5**, while light sources **1**, **2**, and **3** correspond to luminaires **101-2**, **101-4**, and **101-6**.

In accordance with operation **701**, wireless device **111** generates a dataset of input data to be used in the discovery process. In some embodiments of the present invention, device **111** initiates the discovery process depicted in FIG. **7** in response to receiving a command (e.g., from its user, from a different data-processing system, etc.) to discover the topology of network **200**. Operation **701** is described in detail below and in regard to FIG. **9**.

In accordance with operation **702**, wireless device **111** initializes all non-anchored nodes to be spatially at an origin point.

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In accordance with operation **703**, wireless device **111** computes the spatial position of each non-anchored light source. A “non-anchored light source” is a luminaire node whose physical location (i.e., “anchored position”) has not yet been determined. Operation **703** is described in detail below and in regard to FIG. **11**.

In accordance with operation **705**, wireless device **111** computes the spatial position of each non-anchored sensor. A “non-anchored sensor” is a sensor node whose physical location (i.e., “anchored position”) has not yet been determined. Operation **705** is described in detail below and in regard to FIG. **13**.

In accordance with operation **707**, wireless device **111** scales the distance between the components (i.e., sensor nodes, luminaire nodes), if needed. Operation **707** is described in detail below and in regard to FIG. **15**.

In accordance with operation **709**, wireless device **111** performs a convergence check in order to determine whether to continue or stop the discovery process. Operation **709** is described in detail below and in regard to FIG. **16**.

In accordance with operation **711**, wireless device **111** presents at least some of the results of the discovery process to the user. For example and without limitation, device **111** can present any or all of the sensor node and/or light source spatial positions within the area discovered, their angular positions, or any part of the information provided by any or all of the sensor nodes, and/or any intermediate information disclosed herein. Device **111** can present any or all of this information on map (e.g., floor plan, etc.), in a list, or in any other format. Device **111** can store any or all of this information (e.g., in a configuration database, etc.). Moreover, device **111** can transmit any or all of the foregoing information to a different data-processing system, such as to a gateway, to a configuration database in the Cloud, and so forth, for various reasons (e.g., storage, processing, presentation to a user, etc.).

Operations in Generating a Data Set: FIGS. **9A** and **9B** depict salient operations of method **701** according to the illustrative embodiment, by which wireless device **111** generates a dataset of input data to be used in the discovery process. As there are three sensor nodes in the illustrative example (i.e., sensor nodes **101-1**, **101-3**, and **101-5**), *J* has a value equal to 3. As there are three light sources (i.e., luminaire nodes **101-2**, **101-4**, and **101-6**), *I* has a value equal to 3.

In accordance with the illustrative embodiment, each sensor node measures the angular positions of at least two light sources and each light source has its angular positions measured by the at least two sensor nodes. As those who are skilled in the art will appreciate after reading this specification, in some embodiments of the present invention not all of the angular positions of the light sources are measured by all of the sensor nodes.

In the explanation below, the sequence in which the light is measured is based on the lighting being first on, then off. As those who are skilled in the art will appreciate after reading this specification, in some embodiments of the present invention the sequence of lighting measurements can be performed instead as first off, then on. In other words, operation **903** can involve turning off all light sources and operation **915** can involve turning on light source *i*, followed by operation **927** resetting light source *i* by turning it off.

In accordance with operation **901** in FIG. **9A**, wireless device **111** stores the angular orientation of each sensor node. The angular orientation is known because of the way that the sensor node is originally installed physically in building **100**. For example and without limitation, the angu-

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lar orientation of a sensor node can be defined with respect to the x-y plane of an area (e.g., a room, etc.) within building **100**. The angular orientation information for each sensor node enables positions to be referenced with respect to the plane of the area being discovered, rather than with respect to each individual sensor node.

Wireless device **111** also sets “*I*” as being equal to the number of light sources and “*J*” as being equal to the number of sensors.

In accordance with operation **903**, wireless device **111** transmits a signal to all of the light sources to turn on (i.e., to emit light). The indices *i* and *j* are initialized at operations **905** and **907**, respectively.

In accordance with operation **909**, wireless device **111** transmits a first signal to sensor node *j* to make measurements. The operations performed by sensor node *j* are described below and in FIG. **10**.

In accordance with operation **913**, if all *J* sensor nodes have been queried in regard to light source *i*, control of task execution proceeds to operation **915**. Otherwise, control of execution proceeds back to operation **909**.

In accordance with operation **915**, wireless device **111** transmits a signal to light source *i* to turn off (i.e., to stop emitting light). The index *j* is then re-initialized at operation **917**.

In accordance with operation **919**, wireless device **111** transmits a second signal to sensor node *j* to make measurements.

In accordance with operation **923**, if all *J* sensor nodes have been queried in regard to light source *i*, control of task execution proceeds to operation **925**. Otherwise, control of execution proceeds back to operation **919**.

In accordance with operation **925**, wireless device **111** receives and stores the angular position (e.g., 291 degrees, etc.) of light source *i* from each of sensors **1** through *J*.

In accordance with operation **927** in FIG. **9B**, wireless device **111** transmits a signal to light source *i* to turn on.

In accordance with operation **931**, if angular positions for all *I* light sources have been obtained, control of task execution proceeds to operation **933**. Otherwise, control of execution proceeds back to operation **907**.

In accordance with operation **933**, wireless device **111** optionally stores the anchored spatial positions (e.g., $x=500$ units, $y=300$ units, etc.) of selected components that is, of sensor nodes and/or light sources.

In accordance with operation **935**, wireless device **111** optionally stores the distances (e.g., 70 units, etc.) between selected pairs of components.

In accordance with operation **937**, wireless device **111** in some embodiments stores the maximum distances in *x* and *y* coordinates for the set of nodes being discovered. For example, this information is needed if the anchored spatial positions for less than two components are known.

After operation **937**, control of task execution proceeds to operation **703**.

Operation in Determining an Angular Position of a Light Source with Respect to a Sensor Node: FIG. **10** depicts salient operations of method **1000** according to the illustrative embodiment, by which sensor node **101-1** generates and provides a measurement of a light source in relation to the sensor node, wherein the sensor node generates the measurement based on one or more individual measurements (e.g., of light level, etc.) that it makes.

In accordance with the illustrative embodiment, the measurement that sensor node **101-1** provides is that of an angular position of a light source in relation to the sensor node. As those who are skilled in the art will appreciate after

reading this specification, in some alternative embodiments of the present invention the measurement that sensor node **101-1** provides is that of a different characteristic (e.g., location, etc.) of a light source in relation to the sensor node.

In accordance with operation **1001**, sensor node **101-1** receives a first signal, which corresponds to the signal transmitted by wireless device **111** in accordance with operation **909**.

In accordance with operation **1003**, and in response to receiving the first signal, sensor node **101-1** measures light levels sensed by at least three photocells **601** in photocell matrix **533** at a first time, which can be a point in time or part of a finite interval of time. For instance, the measuring occurs when light source *i* is on at the first time. The measuring results in a plurality of first measurements. The first measurements are made from illuminance signals that represent the light levels sensed by photocells **601** at the first time, and wherein the three photocells are arranged such that at least two photocells are along each of a first dimension and a second dimension of the photocell matrix.

In accordance with the illustrative embodiment, the measured values are generated in accordance with the following equations:

$$BX_{LEFT-T1} = \log(X_{LEFT-T1}), \quad (\text{Eq. 1})$$

$$BX_{RIGHT-T1} = \log(X_{RIGHT-T1}), \quad (\text{Eq. 2})$$

$$BY_{DOWN-T1} = \log(Y_{DOWN-T1}), \quad (\text{Eq. 3})$$

$$BY_{UP-T1} = \log(Y_{UP-T1}), \quad (\text{Eq. 4})$$

wherein:

$X_{LEFT-T1}$ is a measurement made at a first time from illuminance signals comprising those received from at least one of photocells **601-1**, **601-4**, and **601-7**.

$X_{RIGHT-T1}$ is a measurement made at a first time from illuminance signals comprising those received from at least one of photocells **601-3**, **601-6**, and **601-9**.

$Y_{DOWN-T1}$ is a measurement made at a first time from illuminance signals comprising those received from at least one of photocells **601-1**, **601-2**, and **601-3**.

Y_{UP-T1} is a measurement made at a first time from illuminance signals comprising those received from at least one of photocells **601-7**, **601-8**, and **601-9**.

$BX_{LEFT-T1}$, $BX_{RIGHT-T1}$, $BY_{DOWN-T1}$, and BY_{UP-T1} are the logarithmic values of $X_{LEFT-T1}$, $X_{RIGHT-T1}$, $Y_{DOWN-T1}$, and Y_{UP-T1} , respectively.

Sensor node **101-1** performs at least some of the measurement processing in the log domain, in order to reduce errors. As those who are skilled in the art will appreciate after reading this specification, in some embodiments of the present invention the measurements can be preserved and processed in the linear domain instead.

As those who are skilled in the art will appreciate after reading this specification, measurements from more than one photocell can be combined (e.g., averaged, etc.) in order to form a representative measurement of a given direction (i.e., X_{LEFT} , X_{RIGHT} , Y_{DOWN} , Y_{UP}). In some embodiments of the present invention, measurements from only an interior portion of photocells **601** in photocell matrix **533** are used. In other words, photocells **601-1** through **601-9** might actually be the interior portion of photocells, wherein at least one or more lines of photocells might border one or more of photocells **601-1** through **601-9** on their exterior.

In accordance with operation **1005**, sensor node **101-1** receives a second signal, which corresponds to the signal transmitted by wireless device **111** in accordance with operation **919**.

In accordance with operation **1007**, and in response to receiving the second signal, sensor node **101-1** measures light levels sensed by at least three photocells **601** in photocell matrix **533** at a second time, which can be a point in time or part of a finite interval of time. For instance, the measuring occurs when light source *i* is off at the second time. The measuring results in a plurality of second measurements. The second measurements are made from illuminance signals that represent the light levels sensed by photocells **601** at the second time. The first and second times are different from each other.

In accordance with the illustrative embodiment, the measured values are generated in accordance with the following equations:

$$BX_{LEFT-T2} = \log(X_{LEFT-T2}), \quad (\text{Eq. 5})$$

$$BX_{RIGHT-T2} = \log(X_{RIGHT-T2}), \quad (\text{Eq. 6})$$

$$BY_{DOWN-T2} = \log(Y_{DOWN-T2}), \quad \text{and} \quad (\text{Eq. 7})$$

$$BY_{UP-T2} = \log(Y_{UP-T2}), \quad (\text{Eq. 8})$$

wherein:

$X_{LEFT-T2}$ is a measurement made at a second time from illuminance signals comprising those received from at least one of photocells **601-1**, **601-4**, and **601-7**.

$X_{RIGHT-T2}$ is a measurement made at a second time from illuminance signals comprising those received from at least one of photocells **601-3**, **601-6**, and **601-9**.

$Y_{DOWN-T2}$ is a measurement made at a second time from illuminance signals comprising those received from at least one of photocells **601-1**, **601-2**, and **601-3**.

Y_{UP-T2} is a measurement made at a first second from illuminance signals comprising those received from at least one of photocells **601-7**, **601-8**, and **601-9**.

$BX_{LEFT-T2}$, $BX_{RIGHT-T2}$, $BY_{DOWN-T2}$, and BY_{UP-T2} are the logarithmic values of $X_{LEFT-T2}$, $X_{RIGHT-T2}$, $Y_{DOWN-T2}$, and Y_{UP-T2} , respectively.

In some alternative embodiments of the present invention, sensor node **101-1** measures the light levels at the second time based on a timer instead of based on receiving the second signal. For instance, the timer can either be provided by wireless device **111** (e.g., in the first signal, etc.) or can be hardcoded in the sensor node with a value that is sufficient to ensure that the two sets of measurements (i.e., first measurements and second measurements) occur under different light conditions (i.e., light turned on and light turned off).

In accordance with operation **1009**, sensor node **101-1** computes a first measured angle (e.g., a direction angle, etc.) across the first and second dimensions from a first difference between at least one of the first measurements made in accordance with operation **1003** and at least one of the second measurements made in accordance with operation **1007**.

In accordance with the illustrative embodiment, the first difference and other differences are generated in accordance with the following equations:

$$dX_{LEFT} = BX_{LEFT-T2} - BX_{LEFT-T1}, \quad (\text{Eq. 9})$$

$$dX_{RIGHT} = BX_{RIGHT-T2} - BX_{RIGHT-T1}, \quad (\text{Eq. 10})$$

$$dY_{DOWN} = BY_{DOWN-T2} - BY_{DOWN-T1}, \quad \text{and} \quad (\text{Eq. 11})$$

$$dY_{UP} = BY_{UP-T2} - BY_{UP-T1}, \quad (\text{Eq. 12})$$

The first angle is generated in accordance with the following equation:

$$\text{Angle} = \arctan((dY_{UP} - dY_{DOWN}) / (dX_{RIGHT} - dX_{LEFT})). \quad (\text{Eq. 13})$$

In accordance with operation **1011**, sensor node **101-1** transmits a first output signal that represents the first measured angle.

Operations in Computing the Spatial position of Each Non-Anchored Light Source: FIG. **11** depicts salient operations of method **703** according to the illustrative embodiment, by which wireless device **111** computes the spatial position of each non-anchored light source.

In accordance with operations **1101** and **1103**, wireless device **111** initializes counters *i* and *j*.

In accordance with operation **1105**, wireless device **111** computes current angle *C* (e.g., a direction angle, etc.) of the direction toward the current position of light source *i* in relation to the current position of sensor *j*. As depicted in FIG. **12**, the current position of light source *i* is at spatial position **1201**, and the current positions of sensor nodes **101-1**, **101-3**, and **101-5** are also depicted.

In accordance with operation **1106**, and referring to FIG. **12**, wireless device **111** computes the delta angle *D* between (i) the measured angle of the direction toward non-anchored light source *i* from sensor node *j*, obtained in accordance with operation **701**, and (ii) current angle *C* that is computed in accordance with operation **1105**. The measured angle points in the direction (i.e., defines the direction) from sensor node *j* to non-anchored light source *i* at aim position **1211-2**. As depicted, the delta angles from the perspective of sensor nodes **101-1**, **101-3**, and **101-5** are delta angles **1202-1**, **1202-2**, and **1202-3**, respectively.

In accordance with operation **1107**, wireless device **111** generates an estimate of the position resulting by moving light source *i* by the delta angle computed in accordance with operation **1106**. As depicted, these estimates of position of light source *i* as they correspond to sensor nodes **101-1**, **101-3**, and **101-5** are position estimates **1203-1**, **1203-2**, and **1203-3**, respectively.

In accordance with operation **1113**, if all sensor nodes have been considered, wireless device **111** generates updated light source position **1204** of light source *i* based on one or more of the estimates of position generated in accordance with operation **1107**. Otherwise, control of task execution proceeds back to operation **1105** to process the next sensor node.

In some embodiments of the present invention, the estimates of position define the vertices of a first polygon, and the updated light source position is defined by the geometric center, or centroid, of the first polygon (e.g., the light source is placed at, or near, the geometric center, etc.). As those who are skilled in the art will appreciate after reading this specification, the updated light source position can be placed at, or near, a different type of center (e.g., circumcenter, incenter, orthocenter, N-point center, etc.)

In accordance with operation **1115**, wireless device **111** moves the position of light source *i* to the updated light source position generated in accordance with operation **1113**. In other words, the updated light source position of light source *i* for the current iteration of processing becomes the current light source position of light source *i* for the next iteration of processing. In some embodiments of the present invention, if all sensor nodes and light source *i* have the same position (e.g., in the initial iteration, etc.), light source *i* is moved away (e.g., by one unit) in the direction indicated by any sensor node.

If all light sources have been considered, control of task execution proceeds to operation **705**. Otherwise, control of task execution proceeds back to operation **1103** to process the next light source.

Operations in Computing the Spatial position of Each Non-Anchored Sensor Node: FIG. **13** depicts salient operations of method **705** according to the illustrative embodiment, by which wireless device **111** computes the spatial position of each non-anchored sensor node.

In accordance with operations **1301** and **1303**, wireless device **111** initializes counters *i* and *j*.

In accordance with operation **1305**, wireless device **111** computes current angle *C* (e.g., a direction angle, etc.) of the direction toward the current position of sensor *j* in relation to the current position of light source *i*. As depicted in FIG. **14**, the current position of sensor *j* is at spatial position **1401**, and the current positions of light sources **101-2**, **101-4**, and **101-6** are also depicted.

In accordance with operation **1306**, and referring to FIG. **14**, wireless device **111** computes the delta angle *D* between (i) the measured angle of the direction toward non-anchored sensor node *j* from light source *i*, obtained in accordance with operation **701**, and (ii) current angle *C* that is computed in accordance with operation **1305**. The measured angle points in the direction (i.e., defines the direction) from light source *i* to non-anchored sensor node *j* at aim position **1411-1**. As depicted, the delta angles from the perspective of light sources **101-2**, **101-4**, and **101-6** are delta angles **1402-1**, **1402-2**, and **1402-3**, respectively.

In accordance with operation **1307**, wireless device **111** generates an estimate of the position resulting by moving sensor node *j* by the delta angle computed in accordance with operation **1306**. As depicted, these estimates of position of sensor node *j* as they correspond to light sources **101-2**, **101-4**, and **101-6** are position estimates **1403-1**, **1403-2**, and **1403-3**, respectively.

In accordance with operation **1313**, if all light sources have been considered, wireless device **111** generates updated sensor node position **1404** of sensor node *j* based on one or more of the estimates of position generated in accordance with operation **1307**. Otherwise, control of task execution proceeds back to operation **1305** to process the next light source.

In some embodiments of the present invention, the estimates of position define the vertices of a first polygon, and the updated sensor node position is defined by the geometric center, or centroid, of the first polygon (e.g., the sensor node is placed at, or near, the geometric center, etc.). As those who are skilled in the art will appreciate after reading this specification, the updated sensor node position can be placed at, or near, a different type of center (e.g., circumcenter, incenter, orthocenter, N-point center, etc.)

In accordance with operation **1315**, wireless device **111** moves the position of sensor node *j* to the updated sensor node position generated in accordance with operation **1313**. In other words, the updated sensor node position of sensor node *j* for the current iteration of processing becomes the current sensor node position of sensor node *j* for the next iteration of processing.

If all sensor nodes have been considered, control of task execution proceeds to operation **707**. Otherwise, control of task execution proceeds back to operation **1303** to process the next sensor node.

Operations in Scaling the Distances Between the Nodes: FIG. **15** depicts salient operations of method **707** according

to the illustrative embodiment, by which wireless device 111 scales the distances between the components (i.e., sensor nodes and light sources).

In accordance with operation 1501, if there are fewer than two components that are anchored (i.e., their locations are known ahead of the discovery process), control of task execution proceeds to operation 1503. Otherwise, control of task execution proceeds to operation 709.

In accordance with operation 1503, wireless device 111 computes the maximum and minimum X and Y coordinates of the set of all of the components, which are referred to as X_{MAX} , X_{MIN} , Y_{MAX} , Y_{MIN} .

In accordance with operation 1505, wireless device 111 computes a maximum size, S_{MAX} , of the component layout based on the maximum and minimum coordinates of the set of all of the components, according to the equation:

$$S_{MAX} = \text{Max}(X_{MAX} - X_{MIN}, Y_{MAX} - Y_{MIN}). \quad (\text{Eq. 14})$$

In accordance with operation 1506, wireless device 111 determines the minimum X and Y and maximum X and Y coordinates, (XRealMin, YRealMin, XRealMax, YRealMax), of a rectangle in which a second polygon is inscribed, wherein the second polygon itself is defined by the topology of the sensor nodes and light source components as the vertices of the polygon. The rectangle is also referred to as a "minimum bounding box." In some embodiments of the present invention, the bounding box is an axis-aligned minimum bounding box.

In accordance with operation 1509, wireless device 111 computes the real maximum size, R_{MAX} , of the component layout, accounting for a floor plan with real distances, according to the equation:

$$R_{MAX} = \text{distance}((X_{RealMin}, Y_{RealMin}), (X_{RealMax}, Y_{RealMax})), \quad (\text{Eq. 15})$$

wherein:

R_{MAX} is the length of the diagonal of the rectangle described above in which the second polygon is inscribed.

In accordance with operation 1511, wireless device 111 adjusts the position coordinates of the components, according to the equations:

$$X = (x - X_{MIN}) * R_{MAX} / S_{MAX}, \text{ and} \quad (\text{Eq. 16})$$

$$Y = (y - Y_{MIN}) * R_{MAX} / S_{MAX}, \text{ and} \quad (\text{Eq. 17})$$

wherein:

X and Y are the corrected coordinates of uncorrected coordinate pair (x,y).

Control of task execution then proceeds to operation 709.

Operations in Performing a Convergence Check: FIG. 16 depicts salient operations of method 709 according to the illustrative embodiment, by which wireless device 111 performs a convergence check to determine whether or not the discovery process has converged sufficiently to a conclusion.

In accordance with operation 1601, wireless device 111 computes an overall shift distance, Distance, based on the shifts of the individual sensor node and light source components. The individual shift reflects the distance between the old and new x-y coordinates of a component in the topology.

In accordance with operation 1603, wireless device 111 checks for convergence based on the relationship $\text{Distance} < \text{Epsilon}$, wherein:

Distance is the overall shift distance computed in accordance with operation 1601,

Epsilon is the expression $\text{Threshold} * \text{Components} * \text{Scale}$,

Threshold is the desired precision in the convergence (e.g., 1×10^{-11} , etc.),

Components is the number of components whose topology is being discovered, and

Scale is a scaling factor.

If the foregoing relationship is met, then the discovery process is deemed to have converged and control of task execution proceeds to operation 711. Otherwise, discovery processing continues and control of task execution proceeds back to operation 703.

It is to be understood that the disclosure teaches just one example of the illustrative embodiment and that many variations of the invention can easily be devised by those skilled in the art after reading this disclosure and that the scope of the present invention is to be determined by the following claims.

What is claimed is:

1. A method comprising:

receiving, by a data-processing system, a first measurement of a first light source in relation to a first sensor, wherein the first measurement is received from the first sensor;

receiving, by the data-processing system, a second measurement of the first light source in relation to a second sensor, wherein the second measurement is received from the second sensor;

generating a first estimate of the position of the first light source, based on a first angle at the first sensor between (i) a first direction toward a current light source position and (ii) a second direction that is defined by the first measurement;

generating a second estimate of the position of the first light source, based on a second angle at the second sensor between (i) a third direction toward the current light source position and (ii) a fourth direction that is defined by the second measurement;

generating an updated light source position of the first light source based on the first estimate and the second estimate; and

presenting the updated light source position of the first light source to a user.

2. The method of claim 1 further comprising:

transmitting, by the data-processing system, a first message to the first sensor, wherein the first measurement is received in response to the transmitting of the first message; and

transmitting, by the data-processing system, a second message to the second sensor, wherein the second measurement is received in response to the transmitting of the second message.

3. The method of claim 1 wherein the first measurement of the first light source is that of an angle in relation to a known, angular orientation of the first sensor.

4. The method of claim 1 wherein the first estimate of the position of the first light source and the second estimate of the position of the first light source define two of the vertices of a first polygon, and wherein the updated light source position of the first light source is defined by the geometric center of the first polygon.

5. The method of claim 4 further comprising:

receiving, by the data-processing system, a third measurement of the first light source in relation to a third sensor; and

generating a third estimate of the position of the first light source, based on a third angle at the third sensor

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between (i) a fifth direction toward the current light source position and (ii) a sixth direction that is defined by the third measurement;

wherein the third estimate of the position of the first light source define a third vertex of the first polygon. 5

6. The method of claim 1 further comprising:

generating a fourth estimate of the position of the first light source, based on a fourth angle at the first sensor between (i) a seventh direction toward a previous light source position and (ii) the second direction, wherein the previous light source position is generated prior to the current light source position; 10

generating a fifth estimate of the position of the first light source, based on a fifth angle at the second sensor between (ii) an eighth direction toward the previous light source position and (ii) the fourth direction; and 15

generating the current light source position of the first light source based on the fourth estimate and the fifth estimate. 20

7. The method of claim 1 further comprising:

receiving, by the data-processing system, a fourth measurement of a second light source in relation to the first sensor;

generating a sixth estimate of the position of the first sensor, based on a sixth angle at the first light source 25

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between (i) a ninth direction toward a current sensor position and (ii) a tenth direction that is defined by the first measurement;

generating a seventh estimate of the position of the first sensor, based on a seventh angle at the second light source between (i) an eleventh direction toward the current sensor position and (ii) a twelfth direction that is defined by the fourth measurement;

generating an updated sensor position of the first sensor based on the sixth estimate and the seventh estimate; and

presenting the updated sensor position of the first sensor to the user.

8. The method of claim 7 further comprising:

transmitting, by the data-processing system, a third message to the first sensor, wherein the fourth measurement is received in response to the transmitting of the third message.

9. The method of claim 7 wherein the updated light source position of the first light source and the updated sensor position of the first sensor define two of the vertices of a second polygon, and further comprising:

adjusting the position coordinates of at least one of the first light source and the first sensor according to the length of a diagonal of a rectangle in which the second polygon is inscribed.

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