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(54) **SATELLITE CONSTELLATION HAVING MULTIPLE ORBITAL INCLINATIONS**

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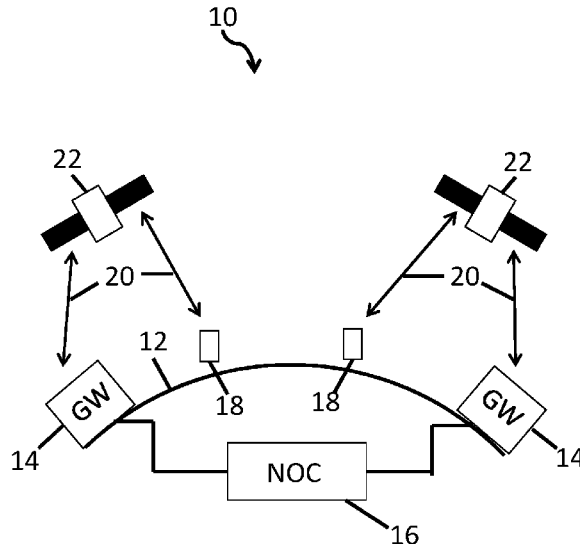
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(57) **ABSTRACT**

A satellite system may have a constellation of communications satellites that provides services to users with electronic devices such as portable electronic devices and home and office equipment. A network operations center may use gateways to communicate with the satellite constellation. The satellite constellation may include sets of satellites with different orbits such as circular orbits with different inclinations, sets of satellites with elliptic orbits, sets of satellites with circular orbits of different altitudes including low earth orbits, medium earth orbits, and/or geosynchronous orbits, and/or sets of satellites with other orbits. The satellite orbits of the satellites in the satellite constellation may be selected to provide coverage to desired user population concentrations at different locations on the earth without using an excessive number of satellites.

**20 Claims, 6 Drawing Sheets**



**Related U.S. Application Data**

continuation of application No. 16/517,265, filed on Jul. 19, 2019, now Pat. No. 10,707,953, which is a continuation of application No. 15/672,136, filed on Aug. 8, 2017, now Pat. No. 10,361,773.

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**B64G 1/10** (2006.01)

(52) **U.S. Cl.**

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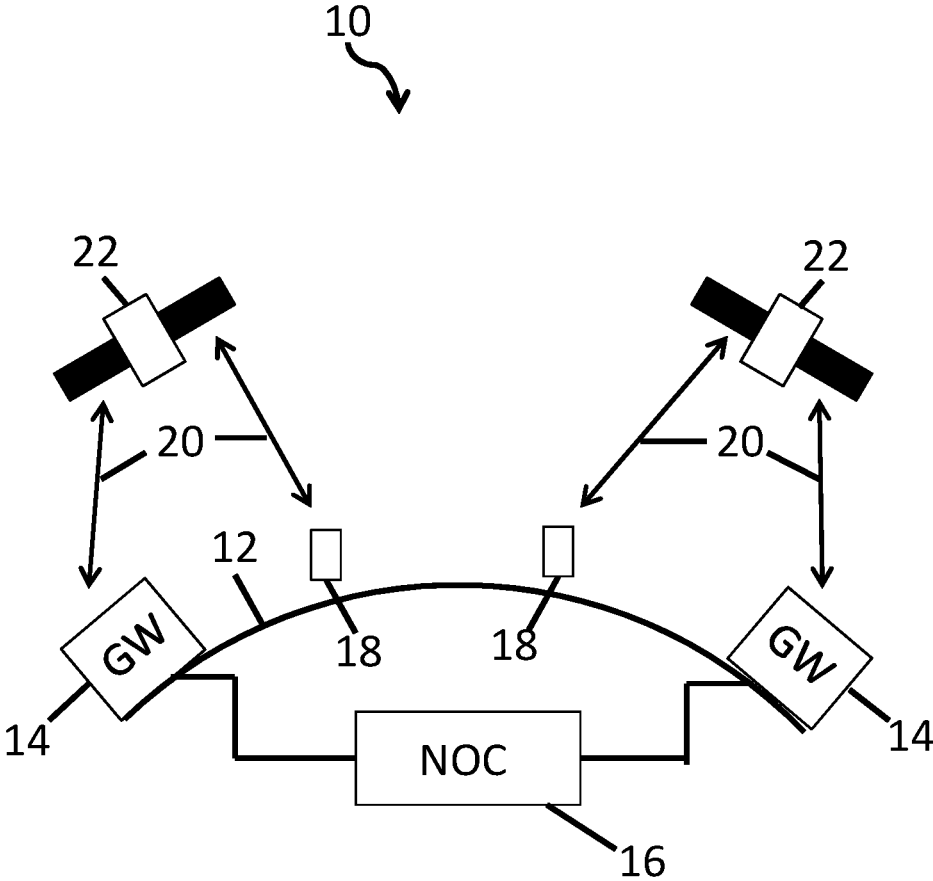


FIG. 1

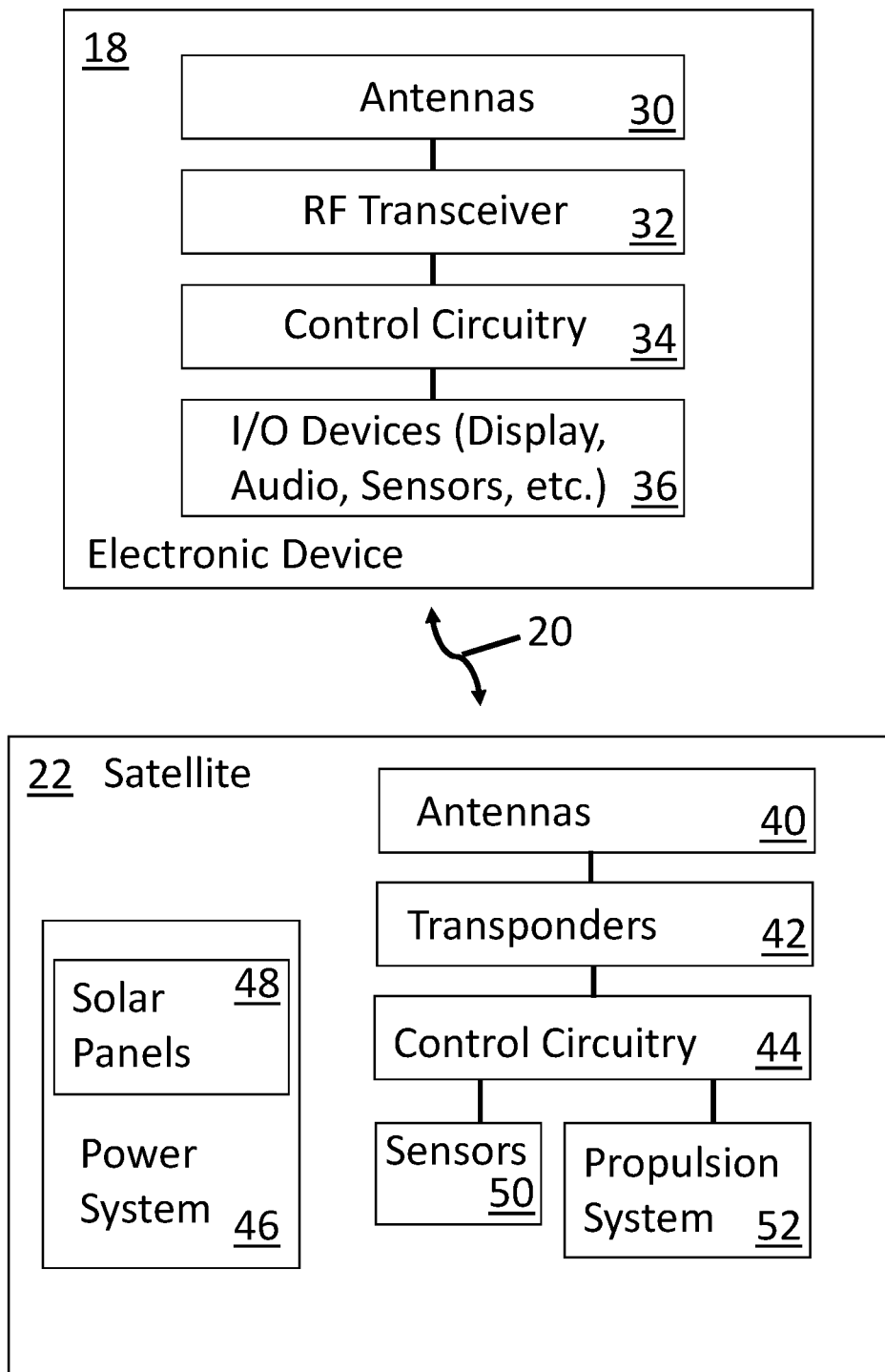


FIG. 2

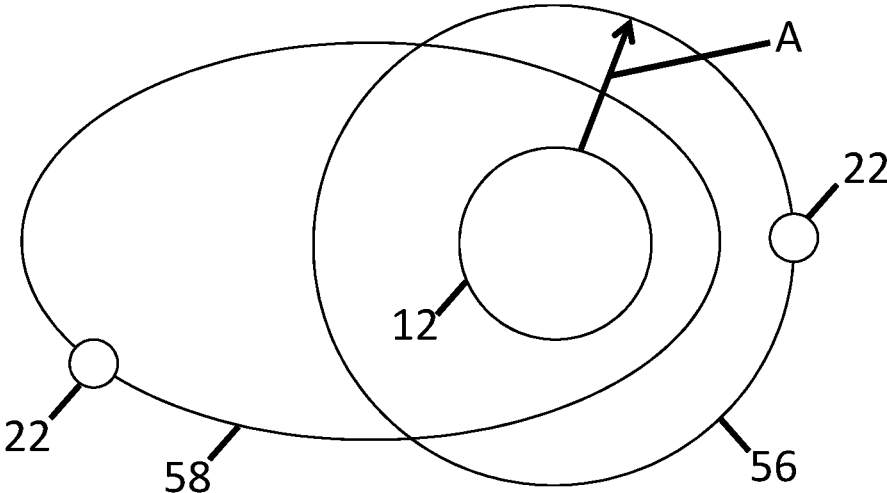


FIG. 3

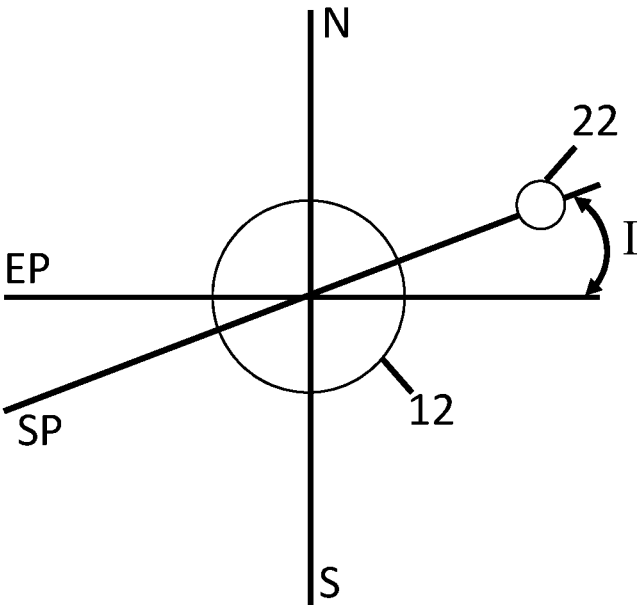


FIG. 4

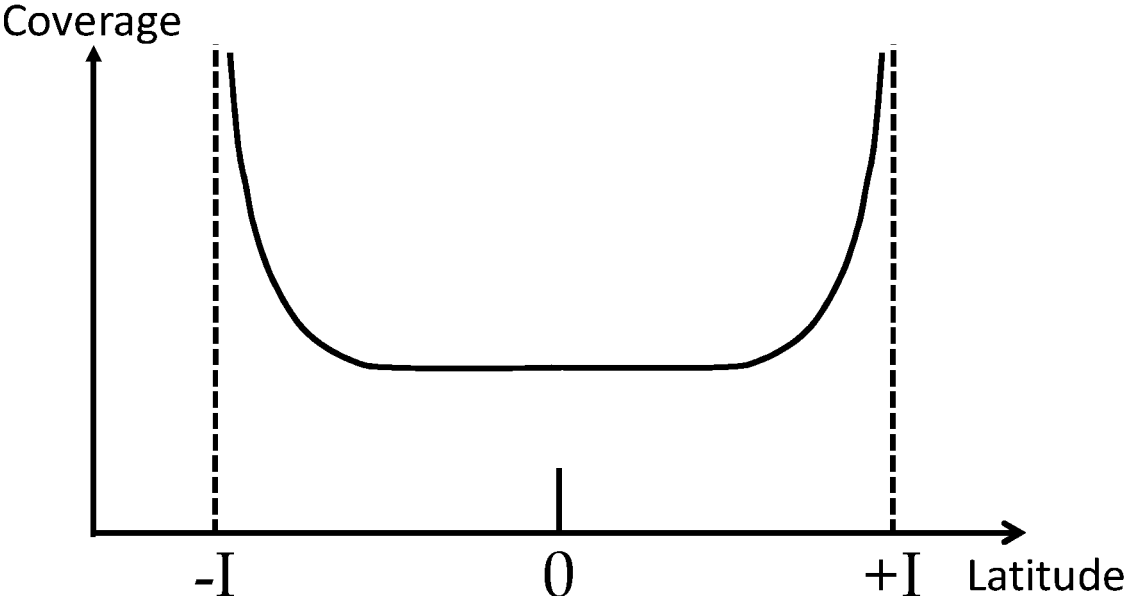


FIG. 5

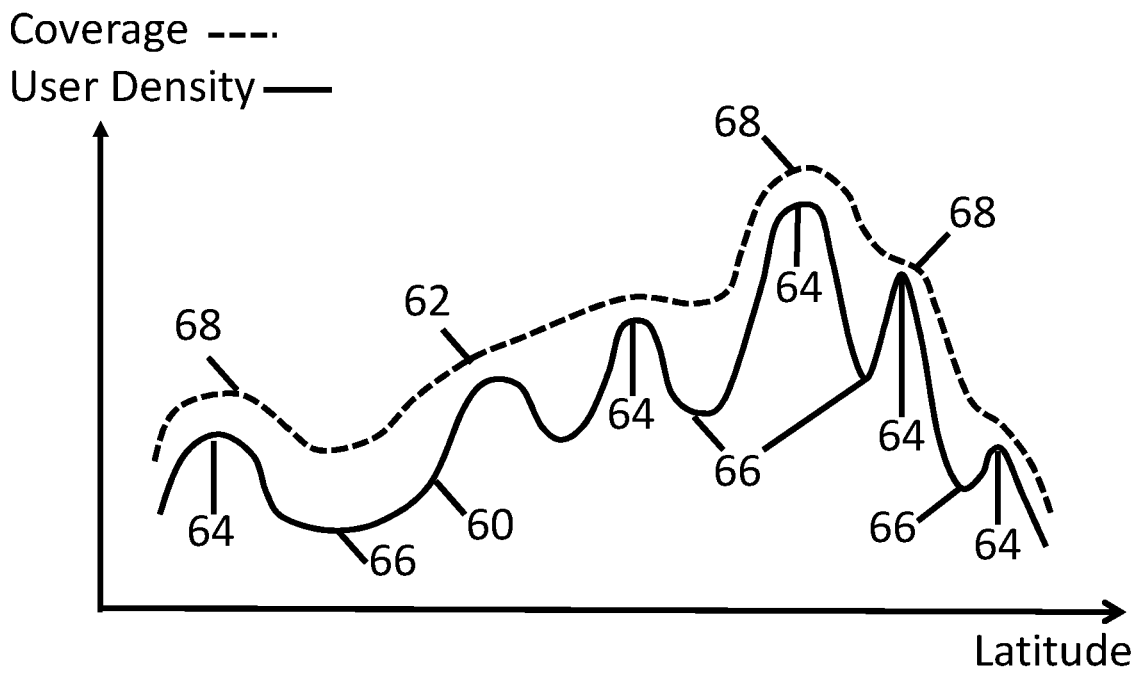


FIG. 6



## SATELLITE CONSTELLATION HAVING MULTIPLE ORBITAL INCLINATIONS

This application is a continuation of U.S. patent application Ser. No. 16/900,721, filed Jun. 12, 2020, which is a continuation of U.S. patent application Ser. No. 16/517,265, filed Jul. 19, 2019, which is a continuation of U.S. patent application Ser. No. 15/672,136, filed Aug. 8, 2017, which claims the benefit of provisional patent application No. 62/489,378, filed on Apr. 24, 2017, each of which is hereby incorporated by reference herein in its entirety.

### FIELD

This disclosure relates generally to satellite communications, including to constellations for satellite communications that include satellites having different inclinations, e.g., to provide different coverage.

### BACKGROUND

Communications systems often use satellites to convey data. Satellite-based systems allow information to be conveyed wirelessly over large distances, such as oceans. For example, satellite-based systems can be used to convey information to land-based devices such as handheld equipment and home or office equipment. Further, satellite communications systems can be used to provide coverage where physical infrastructure has not been installed and/or to mobile devices that do not remain attached to an infrastructure resource.

It can be challenging to implement an effective satellite-based communications system. If care is not taken, satellites may be deployed inefficiently, leading to elevated costs and suboptimal ground coverage. Further, if a satellite-based communications system is designed to serve a period or region of highest demand, resources may remain idle during periods of lower demand and/or over regions with lower demand. Moreover, a conventional satellite-based communication system designed for a particular demand level may not be able to dynamically increase capacity in response to higher demand.

### SUMMARY

A satellite system may have a satellite constellation of communications satellites that provides services (e.g., voice and/or data services) to electronic devices, such as portable electronic devices and home/office equipment. A network operations center may use gateways to communicate with the satellite constellation.

The satellite constellation may include sets of one or more satellites, with each set having different orbits. The satellite constellation may, as an example, include any/all of a set of satellites with circular orbits having different inclinations, a set of satellites with elliptic orbits, a set of satellites with circular orbits of different altitudes including low earth orbits (LEO) (of one or more different altitudes), medium earth orbits (MEO), and/or geosynchronous orbits (e.g., highly inclined geosynchronous orbits), sun synchronous orbits and/or other sets of satellites.

The orbits of the satellites in the satellite constellation may be selected to enhance service efficiency. For example, one or more orbits may be selected to concentrate coverage over user population centers at various locations on the Earth. Additionally or alternatively, one or more orbits may be selected to accommodate peaks in demand that coincide

with particular times of day. Such a design may help reduce the number of satellites needed to provide a desired amount of coverage.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 presents a diagram of an example communications system including satellites, in accordance with some embodiments.

FIG. 2 presents a schematic diagram showing an example of an electronic device in communication with a communications satellite, in accordance with some embodiments.

FIG. 3 presents a diagram of illustrative satellite orbits around the Earth, in accordance with some embodiments.

FIG. 4 presents a diagram of the Earth and an associated inclined satellite orbit, in accordance with some embodiments.

FIG. 5 presents a graph in which coverage (e.g., probability density) for an illustrative satellite with an inclined orbit is plotted as a function of latitude, in accordance with some embodiments.

FIG. 6 presents a diagram showing how user population density may vary as a function of latitude and may exhibit increased density (e.g., peaks) and decreased density (e.g., valleys), and that shows how a satellite constellation may include satellite orbits with multiple different inclinations and other orbital attributes selected to match satellite coverage to user population density, in accordance with some embodiments.

### DETAILED DESCRIPTION

The present disclosure, including the accompanying drawings, is illustrated by way of examples and not by way of limitation.

A communications network may include one or more communications satellites and other equipment, including ground-based communications equipment and user terminals (or user equipment (UE)). One or more of the satellites may be used to deliver wireless services, e.g., to portable electronic devices, home and/or office equipment, and other equipment. For example, wireless services can be provided to handheld devices, wearable devices, set-top boxes, media devices, mobile terminals, computing devices, sensors, etc. An illustrative communications system with satellites is shown in FIG. 1. As shown in FIG. 1, system 10 may include one or more constellations of communications satellites 22. Satellites 22 may be placed in any/all of low earth orbit (LEO) (e.g., at altitudes of 500-1500 km or other suitable altitudes), geosynchronous orbit, and/or medium earth orbit (MEO) around the Earth 12. Satellites 22 may form a satellite constellation having one or more sets of satellites with different types of orbits, e.g., that are synchronized with each other to provide user populations (or geographic regions) with desired amounts of coverage. There may be any suitable number of satellites 22 in the satellite constellation(s) of system 10 (e.g., 10-100, 1,000-10,000, more than 100, more than 1000, fewer than 10,000, etc.).

Satellites 22 may deliver wireless services to equipment such as electronic devices 18. Electronic devices 18 may include handheld devices and/or other mobile devices, such as cellular telephones, tablet computers, laptop computers, wristwatches and other wearable devices, mobile terminals, drones, robots, and other portable electronic devices. Electronic devices 18 may also include stationary (or less portable) equipment, such as set-top boxes (e.g., satellite receivers), routers, home base stations, televisions, desktop

computers, ground terminals (e.g., gateways), and other electronic equipment. Electronic devices **18** may be located anywhere on or above the Earth, e.g., on land, at sea, or in the air. The services provided by satellites **22** may include telephone (voice) service, broadband internet access, media distribution services such as satellite audio (satellite radio and/or streaming audio services) and satellite television (video), data communications, location, and/or other services.

System **10** may include one or more network operations centers (NOCs) such as NOC **16**, which can be coupled to one or more gateways, e.g., gateways **14** (sometimes referred to as ground stations). There may be any suitable number of gateways **14** in system **10** (e.g., 1-100, more than 10, more than 100, fewer than 1000, etc.). Gateways **14** may have transceivers that allow the gateways to transmit wireless signals to satellites **22** over wireless links **20** and that allow the gateways to receive wireless signals from satellites **22** over wireless links **20**. Wireless links **20** may also be used to support communications between satellites **22** and electronic devices **18**. During media distribution operations, for example, a gateway **14** may send traffic over an uplink (one of links **20**) to a given satellite **22** that is then routed via a downlink (one of links **20**) to one or more electronic devices **18**. Gateways **14** may perform a variety of services, including supplying media for electronic devices **18**, routing telephone calls (e.g., voice and/or video calls) between electronic devices **18** and/or other equipment, providing electronic devices **18** with internet access, and/or delivering other communications and/or data services to electronic devices **18**. Gateways **14** may communicate with each other via satellites **22** and/or using ground-based communications networks.

NOC **16** may be used to manage the operations of one or more gateways **14** and/or the operations of one or more satellites **22**. For example, NOC **16** may monitor network performance and take appropriate corrective actions if warranted. During these operations, NOC **16** may update software for one or more satellites **22** and/or electronic devices **18**, may adjust satellite **22** altitude and/or other orbital parameters, may direct one or more satellites **22** to perform operations to adjust satellite solar panels and/or other satellite components, and/or may otherwise control and maintain one or more of the satellites **22** in the constellation of satellites orbiting the Earth **12**. Further, in some embodiments, NOC **16** also may be configured to perform maintenance operations on one or more gateways **14**.

Gateways **14**, satellites **22**, NOC **16**, and electronic devices **18** may be configured to support encrypted communications. For example, NOC **16** and gateways **14** may communicate using encrypted communications. Similarly, gateways **14**, satellites **22**, and electronic devices **18** may communicate using encrypted communications. This allows NOC **16** to issue secure commands and to receive secure information when communicating with gateways **14**, satellites **22**, and/or electronic devices **18**. The use of encrypted communications within system **10** also allows electronic devices **18** to securely communicate with each other and with gateways **14**, and also allows gateways **14** to securely distribute media and/or other information to electronic devices **18**, e.g., in compliance with digital protection requirements.

During operation of system **10**, satellites **22** may serve as orbiting relay stations. For example, when a gateway **14** transmits a wireless uplink signal, one or more satellites **22** may forward these signals as downlink signals to one or more electronic devices **18**. In some embodiments, some

electronic devices **18** may be receive-only devices while other electronic devices **18** may support bidirectional communications with satellites. In scenarios in which an electronic device **18** supports bidirectional communications, an electronic device **18** may transmit wireless signals to one or more satellites **22**, so that the one or more satellites **22** may relay this information to one or more appropriate destinations (e.g., gateways **14**, other electronic devices **18**, etc.).

Satellites **22** and links **20** may support any suitable satellite communications bands (e.g., IEEE bands), such as the L-band (1-2 GHz), S-band (2-4 GHz), C-band (4-8 GHz), Ka-band (27-40 GHz), V-band (40-75 GHz), W-band (75-110 GHz), and/or other bands suitable for space communications (e.g., frequencies above 1 GHz, below 110 GHz, and/or other suitable frequencies).

Some frequencies (e.g., C-band frequencies and other low frequencies such as L-band and S-band frequencies) may penetrate buildings and may therefore be suitable for communicating with electronic devices located indoors at least some of the time, e.g., handheld electronic devices **18** (e.g., devices that are mobile and that may sometimes be indoors and may sometimes be outdoors) and/or electronic devices **18** without an external antenna/receiver. Other frequencies (e.g., V-band frequencies and other high frequencies such as Ka-band and W-band frequencies) do not readily (or effectively) penetrate buildings and may therefore be suitable for communicating with electronic devices **18** that have an external antenna/receiver or that are located outdoors and/or otherwise have a line-of-sight path to satellites **22**. To accommodate a variety of scenarios, e.g., both mobile device scenarios and home/office scenarios, satellites **22** may, for example, include C-band satellites (or other low band satellites such as L-band or S-band satellites), V-band satellites (or other high band satellites such as Ka-band or W-band satellites) and/or dual-band satellites (e.g., satellites that support C-band and V-band communications or other low and high band communications).

In general, population density is not uniform and varies across latitudes. However, satellite resources traditionally have been distributed across latitudes without distinguishing between less populated regions and more densely populated regions. As a result, a constellation organized in such manner requires more satellites (vehicles) to provide coverage over populated areas—thereby providing a surplus of coverage over less densely populated areas. However, efficiencies can be achieved by dividing a constellation of satellites into groups of multiple sub-constellations, each with an inclination and quantity of satellites sized to provide the bulk of its coverage to areas in which the population (e.g., actual population and/or user population) is dense. As a result, use of the constellation's resources can be enhanced as the number of satellites required to provide coverage and capacity is reduced, while excess capacity does not go unused over less populated areas. To ensure an efficient placement of on-orbit satellites, the constellation design can be implemented to match coverage-density with population-density (either actual or user), as closely as possible. For example, a geographic increase (e.g., peak) in population-density (or other such metric) identifies a service area by latitude. In at least some implementations, there can be multiple such service areas. Accordingly, a constellation can employ multiple sets of satellites with different orbital inclinations, e.g., Walker orbit inclinations, to approximate a match of coverage-density to population-density, facilitating an efficient placement of on-orbit satellites.

FIG. **2** presents a schematic diagram of an illustrative electronic device **18** in communication, over a wireless

communications link **20**, with an illustrative satellite **22**. As shown in FIG. **2**, electronic device **18** may include one or more antennas **30**. Antennas **30** may include monopoles, dipoles, and/or other types of antenna elements. Antennas **30** may, for example, include loop antennas, helical antennas, patch antennas, inverted-F antennas, Yagi antennas, slot antennas, horn antennas, cavity antennas, dish antennas, arrays of antennas (e.g., a phased antenna array that supports beam steering operations), or other suitable antennas. The antennas **30** can be implemented such that they are suitable for communication with one or more satellites using one or more satellite communications bands. Radio-frequency transceiver circuitry **32** may include radio-frequency receiver circuitry and/or radio-frequency transmitter circuitry that allows electronic device **18** to transmit and/or receive wireless signals over wireless communications link **20** using one or more antennas **30**. Electronic device **18** may also include control circuitry **34** and input-output devices **36**. Control circuitry **34** may include storage, such as solid-state drives, random-access memory, and/or hard disk drives and other volatile and/or nonvolatile memory. Control circuitry **34** may also include one or more microcontrollers, microprocessors, digital signal processors, communications circuits with processors, application specific integrated circuits, programmable logic devices, field programmable gate arrays, and/or other processing circuitry. During operation, control circuitry **34** may run code (instructions) that is stored in the storage of control circuitry **34** to implement desired functions for electronic device **18**.

Control circuitry **34** may use input-output devices **36** to supply output to an interface configured to render output perceivable by a user and/or to external equipment, and may gather input received from a user and/or external source(s). Input-output devices **36** may include displays configured to present images, audio devices (e.g., speakers and/or microphones), sensors, controls, and other components. For example, input-output devices **36** may include user input devices such as one or more buttons, touch screens, sensors (e.g., accelerometers and/or gyroscopes), microphones for gathering voice commands, and/or other components for gathering input from a user. Further, input-output devices **36** may include speakers, light-emitting components, displays, vibrators and/or other haptic output devices, and other equipment for supplying a user with output. Input-output devices **36** may include sensors such as force sensors, position sensors, gyroscopes, magnetic sensors, accelerometers, capacitive touch sensors, proximity sensors, ambient light sensors, temperature sensors, moisture sensors, gas sensors, pressure sensors, and other sensors for gathering information representative of the environment in which electronic device **18** is located.

A satellite, such as satellite **22**, may include one or more antennas **40**. Antennas **40** may be based on any suitable type(s) of antenna elements (e.g., antenna elements such as monopoles or dipoles, loop antennas, helical antennas, patch antennas, inverted-F antennas, Yagi antennas, slot antennas, horn antennas, cavity antennas, etc.). Antennas **40** may be used in any suitable type(s) of antenna arrays (e.g., phased antenna arrays, fixed direct radiating arrays, deployable direct radiating antenna arrays, space fed arrays, reflector fed arrays, etc.). The antennas **40** can be implemented such that they are suitable for communication with one or more electronic devices **18**, gateways **14**, or other communication devices/nodes using one or more satellite communications bands.

Satellite **22** may include transceiver circuitry that is communicatively coupled (directly or indirectly) to antennas

**40**. The transceiver circuitry may include one or more components, such as one or more transponders **42** for receiving uplink signals and transmitting downlink signals, e.g., over links **20**. Further, control circuitry **44** may be used to control the operation of satellite **22**. Control circuitry **44** may include storage and/or processing circuits of the type used in control circuitry **34**.

Power may be supplied to satellite **22** from power system **46**. Power system **46** may include one or more solar panels **48** (or arrays of solar panels) for converting energy from the sun into electrical power. Power system **46** may include power regulator circuitry and batteries for storing electrical power generated by solar panels **48**, and for distributing power to the components of satellite **22**. Control circuitry **44** may receive information from one or more sensors **50**. Further, control circuitry **44** may receive commands from NOC **16** and, using information from one or more sensors and/or received commands, may perform maintenance and/or control operations (e.g., software updates, operations related to the deployment and operation of solar panels **48**, diagnostic routines, altitude adjustments and other orbital adjustments using propulsion system **52**, etc.). Sensors **50** may include light-based sensors (e.g., infrared cameras, visible light cameras, etc.), lidar, radar, sensors that measure backscattered light and/or backscattered radio-frequency signals, temperature sensors, radiation sensors, accelerometers, gyroscopes, magnetic sensors, spectrometers, and/or other sensors. Sensors **50** may be used in performing remote sensing operations, fault detection, satellite positioning, and other operations.

It may be desirable for the constellation of satellites **22** in system **10** to include satellites with different types of orbits. As an example, satellites **22** may include orbits with different altitudes, eccentricities, inclinations, and other orbital attributes. One or more sun synchronous satellites (or a satellite in a sun synchronous orbit) may be included in the constellation of satellites **22** in system **10**. The one or more sun synchronous satellites can be configured to help meet demand (e.g., as measured in throughput, the number of simultaneous connections, or other such measures) during a high-demand period, such as during an afternoon or evening period. By combining different orbital types within the same satellite constellation, satellite resources can be deployed with enhanced efficiency.

FIG. **3** is a diagram of two illustrative satellite orbits (geocentric orbits) about the Earth **12**. A satellites **22** may orbit in a circular orbit as shown by illustrative circular orbit **56** or in an elliptic orbit such as elliptic orbit **58**. A circular orbit is characterized by an eccentricity of 0. An elliptical orbit has an eccentricity of greater than 0.

A satellite in a circular orbit may be characterized by an orbital altitude  $A$ , as shown in FIG. **3**. Satellites **22** may orbit at any altitude suitable for their intended purpose. For example, a satellite **22** may orbit Earth **12** in low earth orbit (e.g., at an altitude  $A$  of 500-1500 km), in geosynchronous orbit (at an altitude  $A$  of approximately 35,800 km), or in medium earth orbit (e.g., between low earth orbit and geosynchronous orbit). Examples of medium earth orbits include semi-synchronous orbits and Molniya orbits. Semi-synchronous orbits have an altitude of about 20,000 km and are characterized by an orbital period of one half of one sidereal day. A Molniya orbit has an eccentricity of greater than zero and a perigee location in the Southern Hemisphere so a satellite in this type of orbit will spend most of its orbital time above the Northern Hemisphere or vice versa. A Tundra orbit is an elliptical orbit (with an eccentricity greater than zero) that has twice the orbital period of

a Molniya orbit. Other elliptical orbits may be used, if desired (e.g., orbits with eccentricities of at least 0.3, at least 0.5, at least 0.7, less than 0.8, etc.).

If desired, a satellite may have an inclined circular orbit (a circular orbit out of the equatorial plane). Consider, as an example, satellite **22** of FIG. **4**. In the diagram of FIG. **4**, satellite **22** is orbiting about Earth **12** in satellite orbital plane SP. Plane SP is inclined at inclination (inclination angle) *I* with respect to equatorial plane EP, which is a plane that is aligned with the Earth's equator. Polar orbits (sometimes referred to as nearly polar orbits) are orbits that pass over the north and south poles and are therefore characterized by inclinations of about 90° (e.g., at least 85°, at least 88°, at least 89°, 90°, less than 90°, or other suitable polar orbit inclination).

One or more of satellites **22** in the satellite constellation of system **10** may have a sun synchronous orbit. Sun synchronous orbits (heliosynchronous orbits) are polar orbits (near polar orbits) that pass the equator (or other given latitude) at the same local time each day. The altitude and inclination of a sun synchronous orbit are such that the nodal regression rate matches the Earth orbit rate. As a result, to a user on the ground, a sun synchronous satellite will pass overhead at the same time of day each day. Because satellites with sun synchronous orbits are available to handle communications traffic at the same local time each day, the inclusion of one or more sun synchronous satellites in the satellite constellation of system **10** may help the satellite constellation to efficiently meet peak traffic demands.

In general, each type of orbit that is included in the satellite constellation of system **10** may help augment the performance of the constellation in a different way. For example, an elliptic orbit such as Molniya or Tundra orbit may be used to provide capacity to a user population center at a particular longitude and/or latitude (or range(s) thereof) in the Northern or Southern Hemisphere (e.g., a population center in Europe, North America, Australia, or Asia). Further, sun synchronous orbits may be used to provide capacity that is concentrated on one or more high-demand times of day (e.g., mornings or evenings). Inclined circular orbits may be used to provide coverage over a desired range of latitudes. Low-earth orbits may help reduce latency (e.g., for traffic that involves voice telephone calls and other latency-sensitive traffic) and may help reduce transmit and receive powers. Medium-earth orbits and geosynchronous orbits may help increase coverage, reducing the total number of satellites needed to service a given region and may be well suited to broadcast-type traffic (e.g., media distribution services such as television services, music services, etc.).

Consider, as an example, a satellite with an inclined circular orbit. An example of the coverage (probability density) of a satellite with an inclination *I* as a function of latitude is illustrated in FIG. **5**. As illustrated in FIG. **5**, coverage for an inclined orbit is concentrated near +*I* and -*I*. This attribute of an inclined orbit allows the corresponding coverage to be selectively concentrated over one or more latitudes, e.g., latitudes associated with increased demand, such as user population centers (user traffic concentrations). By using sets of satellites, each of which is associated with a particular inclination, multiple areas of relatively higher demand (e.g., user population centers) at multiple respective different latitudes may be served. If, as an example, user populations are concentrated at latitudes of 55°, 48°, 40°, and 33°, the satellite constellation of system **10** may include a first group of *N*<sub>1</sub> satellites **22** with orbits having an inclination of 55°, a second group of *N*<sub>2</sub> satellites **22** with orbits having an inclination of 48°, a third group of *N*<sub>3</sub>

satellites **22** with orbits having an inclination of 40°, and a fourth group of *N*<sub>4</sub> satellites **22** with orbits having an inclination of 33°.

As illustrated by solid line **60** in the graph of FIG. **6**, an exemplary user population density may be characterized by one or more peaks **64** and one or more valleys **66** at different latitudes. By adjusting the numbers of satellites at each corresponding inclination (e.g., the values of *N*<sub>1</sub>, *N*<sub>2</sub>, *N*<sub>3</sub>, and *N*<sub>4</sub> in the preceding example), a satellite coverage (probability density) curve, such as dashed line curve **62** of FIG. **6** may be produced that has one or more peaks **68** that partly or fully overlap peaks **64** and thereby help accommodate the variations in user population density **60**. By varying the numbers of satellites **22** with orbits at each of multiple different inclinations, the total number of satellites **22** may be reduced in the satellite constellation. If desired, efficiency may be further enhanced by incorporating satellites with non-circular orbits, polar orbits such as sun synchronous orbits, medium earth orbits, and/or geosynchronous orbits into the satellite constellation. The use of a constellation that includes satellites with inclined circular orbits at multiple different inclinations is merely illustrative.

Within the constellation of satellites **22** in system **10**, each group of satellites **22** that share a common orbit (e.g., a common orbital inclination and altitude for a set of low earth orbiting satellites with circular orbits, a common elliptical orbital type for a set of medium earth orbit satellites, a geocentric orbit, etc.), may include any suitable number *N* of satellites **22**. For example, *N* may be 1-100, 10-1000, 10-10,000, 20-500, at least 10, at least 50, at least 100, at least 200, fewer than 10,000, fewer than 1000, fewer than 500, fewer than 100, or other suitable number.

Satellites **22** in the constellation of satellites may have the same types of antenna arrays (with the same types of antenna elements), may have different types of antennas (e.g., one type of antenna array may be used for low earth orbit satellites, another type of antenna array may be used for sun synchronous satellites, and another type of antenna array may be used for geosynchronous satellites), may have different types of power systems (e.g., different power sources, different numbers of solar panels per satellite, etc.), or may have a common type of power system (e.g., a power system that has the same type and number of solar panels, etc.), may have different satellite buses or may share a common satellite bus architecture, may have different propulsion systems, may share a common type of propulsion system, etc. The satellites in the satellite constellation of system **10** may be communications satellites (e.g., satellites that handle voice and data traffic, audio and/or video media broadcasts such as broadcasts of television traffic, and/or that handle other suitable types of communications traffic). Different sets of satellites (having the same or different components) may have different eccentricities, altitudes (e.g., different circular low earth orbit altitudes or other different circular orbit altitudes such as lower altitudes to minimize latency and higher altitudes to enhance capacity by covering larger areas on the ground per satellite), inclinations, and/or other different orbital attributes. For example, one, two, three, four, or five or more sets of satellites may have circular low earth orbits with different respective inclinations (e.g., inclinations of 0-80°, 10-60°, 30-60°, more than 30° less than 80°, less than 60°, less than 70°, or other suitable inclinations) and one, two, three, four, or five or more of these orbits may have altitudes that are under a given altitude, whereas one or more additional sets of satellites may have altitudes that are greater than the given altitude. If desired, one or more of these additional sets of

satellites may be geosynchronous and one or more of these additional sets of satellites may be characterized by medium earth orbits. Geosynchronous orbits may include inclined geosynchronous orbits (e.g., to enhance coverage at higher latitudes). One or more sets of satellites with one or more different respective elliptic orbits (different respective eccentricities) may be included in the satellite constellation, if desired. Some of the satellites (e.g., satellites with inclined geosynchronous orbits or other orbits) may have storage that caches popular media content (e.g., news headlines, popular media such as popular movies, etc.). Satellites with cached content and/or other satellites may multicast content (e.g., content may be transmitted to multiple users in parallel). In some instances, content can be multicast around the clock, while in other instances content can be multicast during periods of low utilization, e.g., at night. In some instances, some content can be multicast for immediate consumption, while other content (e.g., applications, software updates, media content) can be multicast for storage (e.g., for caching on devices, such as STBs or UEs), such this it is immediately available on demand.

In accordance with an embodiment, a satellite system is provided that includes a satellite constellation having at least first and second sets of communications satellites having different respective first and second orbital inclinations, gateways configured to communicate with the satellite constellation, and a network operations center configured to communicate with the first and second sets of communications satellites using the gateways.

In accordance with another embodiment, the first and second sets of communications satellites have low earth orbits.

In accordance with another embodiment, the low earth orbits of the first and second sets of communications satellites have altitudes below a first orbital altitude and the satellite constellation has at least a third set of communications satellites having a second orbital altitude that is greater than the first orbital altitude.

In accordance with another embodiment, the third set of communications satellites includes geosynchronous satellites.

In accordance with another embodiment, the third set of communications satellites includes medium earth orbit satellites.

In accordance with another embodiment, the third set of communications satellites includes geosynchronous satellites with inclined geosynchronous orbits.

In accordance with another embodiment, the third set of communications satellites includes satellites with elliptical orbits that are characterized by an eccentricity of at least 0.7.

In accordance with another embodiment, the first set of satellites has low earth orbits and includes satellites with a first altitude and satellites with a second altitude that is different than the first altitude.

In accordance with another embodiment, the first and second sets of communications satellites have low earth orbits with different respective altitudes below a first orbital altitude, the satellite constellation has at least a third set of communications satellites having a second orbital altitude that is greater than the first orbital altitude, and the satellite constellation includes a fourth set of communications satellites having a third orbital altitude that is greater than the second orbital altitude.

In accordance with an embodiment, a satellite constellation is provided that includes first, second, and third sets of communications satellites each with a different circular low earth orbit having a different respective orbital inclination,

and a fourth set of communications satellites, the first, second, and third sets of communications satellites have orbital altitudes that are less than a first orbital altitude and the fourth set of communications satellites has a second orbital altitude that is greater than the first orbital altitude.

In accordance with another embodiment, the fourth set of communications satellites includes geosynchronous satellites.

In accordance with another embodiment, the fourth set of communications satellites includes geosynchronous satellites with inclined orbits.

In accordance with another embodiment, the fourth set of communications satellites includes medium earth orbit satellites.

In accordance with another embodiment, the satellite constellation includes a fifth set of communications satellites having inclined geosynchronous orbits.

In accordance with another embodiment, the satellite constellation includes a fifth set of communications satellites each having an orbital inclination greater than the orbital inclinations of the first, second, and third sets of communications satellites.

In accordance with another embodiment, the satellites constellation includes at least one geosynchronous satellite.

In accordance with an embodiment, a satellite constellation is provided that includes a first set of communications satellites in low earth orbit, each of the communications satellites in the first set of communications satellites is characterized by an inclined circular orbit with a first inclination and a second set of communications satellites in low earth orbit, each of the communications satellites in the second set of communications satellites is characterized by an inclined circular orbit with a second inclination that is different than the first inclination.

In accordance with another embodiment, each of the communications satellites in the first set of communications satellites has a first antenna array formed from first antenna elements of a given type and each of the communications satellites in the second set of communications satellites has a second antenna array formed from second antenna elements of the given type.

In accordance with another embodiment, communications satellites of the first and second sets of communications satellites each have a common number of solar panels.

In accordance with another embodiment, the satellite constellation includes a third set of communications satellites in low earth orbit, each of the communications satellites in the third set of communications satellites is characterized by an inclined circular orbit with a third inclination that is different than the first and second inclinations, and a fourth set of communications satellites in low earth orbit, where each of the communications satellites in the fourth set of communications satellites is characterized by an inclined circular orbit with a fourth inclination that is different than the first, second, and third inclinations and the first, second, third, and fourth sets of communications satellites are configured to communicate with a common network operations center.

The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. A satellite communications system comprising:
  - a network operations center; and
  - at least one gateway configured to route communications between the network operations center and a plurality

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- of user equipment devices on Earth using first, second, and third sets of communications satellites in a satellite constellation, wherein:
  - the communications satellites in the first set of communications satellites are in orbits with a first inclination and with a first orbital altitude,
  - the communications satellites in the second set of communications satellites are in orbits with a second inclination and with a second orbital altitude, the second inclination being different from the first inclination and the second orbital altitude being greater than the first orbital altitude, and
  - the communications satellites in the third set of communications satellites are in orbits with a third inclination and with a third orbital altitude, the third inclination being different from the second inclination and the third orbital altitude being greater than the second orbital altitude.
- 2. The satellite communications system of claim 1, wherein the third orbital altitude is between 500 and 1500 km.
- 3. The satellite communications system of claim 2, wherein the first set of communications satellites comprises at least 1,000 communications satellites, the second set of communications satellites comprises between 20 and 500 communications satellites, and the third set of communications satellites comprises at least 200 and fewer than 1,000 satellites.
- 4. The satellite communications system of claim 3, wherein the first inclination is between 30 degrees and 60 degrees, the second inclination is greater than the first inclination and less than 80 degrees, and the third inclination is between 30 degrees and 60 degrees.
- 5. The satellite communications system of claim 4 wherein the first inclination is 55 degrees and wherein the third inclination is 55 degrees.
- 6. The satellite constellation of claim 4, wherein the first set of communications satellites comprises low earth orbit satellites.
- 7. The satellite constellation of claim 6, wherein the second set of communications satellites comprises low earth orbit satellites.
- 8. The satellite constellation of claim 7, wherein the third set of communications satellites comprises low earth orbit satellites.
- 9. The satellite constellation of claim 4, wherein the orbits with the first inclination are circular orbits.
- 10. The satellite constellation of claim 9, wherein the orbits with the second inclination are circular orbits.
- 11. The satellite constellation of claim 10, wherein the orbits with the second inclination are circular orbits.
- 12. The satellite constellation of claim 4, further comprising a sun-synchronous communications satellite.
- 13. The satellite constellation of claim 4, further comprising a geosynchronous communications satellite.

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- 14. A satellite constellation comprising:
  - a first set of communications satellites in orbits with a first inclination and a first orbital altitude;
  - a second set of communications satellites in orbits with a second inclination and a second orbital altitude, the second inclination being different from the first inclination and the second orbital altitude being different from the first orbital altitude; and
  - a third set of communications satellites in orbits with a third inclination and a third orbital altitude, the third orbital altitude being greater than the second orbital altitude, wherein the first, second, and third sets of communications satellites are configured to route communications between at least one gateway and a plurality of user equipment devices on Earth.
- 15. The satellite constellation of claim 14, wherein the third orbital altitude is between 500 and 1500 km.
- 16. The satellite constellation of claim 14, wherein the first set of communications satellites comprises at least 1,000 communications satellites, the second set of communications satellites comprises between 20 and 500 communications satellites, and the third set of communications satellites comprises at least 200 and fewer than 1,000 satellites.
- 17. The satellite constellation of claim 14, wherein the first inclination is between 30 degrees and 60 degrees, the second inclination is greater than the first inclination and less than 80 degrees, and the third inclination is between 30 degrees and 60 degrees.
- 18. The satellite constellation of claim 17 wherein the first inclination is 55 degrees and wherein the third inclination is 55 degrees.
- 19. A method of operating a satellite constellation, the method comprising:
  - routing, using a first set of satellites, a second set of satellites, and a third set of satellites in the satellite constellation, communications between at least one gateway and a plurality of user equipment devices on Earth, wherein
    - the first set of satellites are in orbits with a first inclination and a first orbital altitude,
    - the second set of communications satellites are in orbits with a second inclination and a second orbital altitude, the second inclination being different from the first inclination and the second orbital altitude being different from the first orbital altitude, and
    - the third set of communications satellites are in orbits with a third inclination and a third orbital altitude, the third orbital altitude being greater than the second orbital altitude.
- 20. The method of claim 19, wherein the third orbital altitude is between 500 and 1500 km.

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