METHODS AND SYSTEMS FOR SCHEDULING THE TRANSMISSION OF LOCALIZATION SIGNALS AND OPERATING SELF-LOCALIZING APPARATUS

Abstract

Localization systems and methods for transmitting timestampable localization signals from anchors according to one or more transmission schedules. The transmission schedules may be generated and updated to achieve desired positioning performance. For example, one or more anchors may transmit localization signals at a different rate than other anchors, the anchor transmission order can be changed, and the signals can partially overlap. In addition, different transmission parameters may be used to transmit two localization signals at the same time without interference. A self-localizing apparatus is able to receive the localization signals and determine its position. The self-localizing apparatus may have a configurable receiver that can select to receive one of multiple available localization signals. The self-localizing apparatuses may have a pair of receivers able to receive two localization signals at the same time. A bridge anchor may be provided to enable a self-localizing apparatus to seamlessly transition between two localization systems.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 18/427,590, filed Jan. 30, 2024, now U.S. Pat. No. 12,262,288, which is a continuation of U.S. patent application Ser. No. 18/099,778, filed Jan. 20, 2023, now U.S. Pat. No. 11,924,719, which is a continuation of U.S. patent application Ser. No. 17/572,303, filed Jan. 10, 2022, now U.S. Pat. No. 11,595,795, which is a continuation of U.S. patent application Ser. No. 16/918,813, filed Jul. 1, 2020, now U.S. Pat. No. 11,259,154, which is a continuation of Ser. No. 16/552,877, filed Aug. 27, 2019, now U.S. Pat. No. 10,721,602, which is a continuation of U.S. patent application Ser. No. 16/167,482, filed Oct. 22, 2018, now U.S. Pat. No. 10,440,533, which is a continuation of U.S. patent application Ser. No. 15/168,122, filed May 30, 2016, now U.S. Pat. No. 10,111,044, which claims the benefit of U.S. Provisional Patent Application No. 62/168,704, filed May 29, 2015, and is a continuation in-part of U.S. patent application Ser. No. 15/063,104, filed Mar. 7, 2016, now U.S. Pat. No. 9,885,773, all of which are hereby incorporated by reference herein in their entireties.

FIELD
[0002] The present disclosure relates to the field of localizing objects. The disclosure also relates to

localization systems and methods that use timestampable signals such as ultra-wideband (UWB) signals. The disclosure further relates to operating self-localizing apparatuses.

BACKGROUND

[0003] Logistics and industrial automation increasingly rely on accurate localization to support and control manual and automated processes, with applications ranging from "smart things" through effective tracking and assistance solutions to robots such as automated guided vehicles (AGVs).

[0004] UWB technology has been advocated as a localization solution suitable for asset tracking applications. Such applications are concerned with maintaining a centralized database of assets and their storage locations in a warehouse, hospital, or factory. When using UWB technology, assets, such as pallets, equipment, or also people may be equipped with tags that emit UWB signals at regular intervals. These signals may then be detected by UWB sensors installed in the warehouse, hospital, or factory. A central server then uses the UWB signals detected by the UWB sensors to compute the tag's location and update the centralized database.

[0005] Mobile robots are increasingly used to aid task performance in both consumer and industrial settings. Autonomous mobile robots in particular offer benefits including freeing workers from dirty, dull, dangerous, or distant tasks; high repeatability; and, in an increasing number of cases, also high performance. A significant challenge in the deployment of mobile robots in general and autonomous mobile robots in particular is robot localization, i.e., determining the robot's position in space. Current localization solutions are not well suited for many mobile robot applications, including applications where mobile robots operate in areas where localization such as that provided by global navigation satellite systems (GNSS) is unreliable or inoperative, or applications that require operation near people.

[0006] Using current UWB localization solutions for robot localization would not enable a mobile robot to determine its own location directly. Rather, a robot equipped with a tag would first emit an UWB signal from its location, UWB sensors in its vicinity would then detect that UWB signal and relay it to a central server that would then compute the mobile robot's location, and then this location would have to be communicated back to the robot using a wireless link. This type of system architecture invariably introduces significant communication delays (e.g., latency) for controlling the mobile robot. This communication architecture also results in a relatively higher risk of lost signals (e.g., due to wireless interference) and correspondingly lower system robustness, which makes it unsuitable for many safety-critical robot applications (e.g., autonomous mobile robot operation). Furthermore, in this architecture the maximum number of tags and the tag emission rate (i.e., the localization system's update rate) are invariably linked because in these systems multiple UWB signals currently do not overlap. This results in limited scalability for a given tag emission rate (i.e., the system can only support a limited number of tags in parallel). In addition, if a higher tag emission rate or redundancy is required, then a smaller number of tags will need to be used. In addition, with such an architecture, the maximum update rate for determining the position of tags is inversely proportional to the number of tags. This is unsuitable for situations where a large number of objects need to be tracked with a high update rate.

[0007] Another localization system proposed in the prior art uses mobile transceivers that communicate with stationary transceivers through the two-way exchange of UWB signals. Two-way communication with a stationary transceiver enables a mobile transceiver to compute the time-of-flight between itself and the stationary transceiver. In this architecture, communication between mobile transceivers and stationary transceivers must be coordinated, such that communications do not interfere. Knowledge of the time-of-flight to three or more stationary transceivers enables each mobile transceiver to compute its relative location within an environment using trilateration. Because each mobile transceiver communicates with each stationary transceiver, the update rate of the system is inversely proportional to the number of mobile transceivers and to the number of stationary transceivers. This architecture is therefore not suitable for systems where a large number of objects must be localized at a high frequency (e.g., tracking a group of robots, where position

measurements are used in the robots' control loops to influence the robots' motions), where a mobile transceiver's position or identity should be kept private (e.g., tracking people), where both transceiver redundancy and high update frequency are desired (e.g., safety critical applications such as positioning systems for vehicles), or in multipath environments, which require a maximum of transceivers to help disambiguate multipath signals, where a high update frequency and a large number of tracked objects are desired (e.g., robot warehouses).

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0008] Embodiments of the present disclosure are illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements and in which:
[0009] FIG. is a block diagram of an illustrative localization system in accordance with some embodiments of the present disclosure;
[0010] FIG. **2** is a block diagram of illustrative transceivers and self-localizing apparatus of a localization system in accordance with some embodiments of the present disclosure;
[0011] FIG. **3** is a detailed block diagram of illustrative transceivers of a localization system in accordance with some embodiments of the present disclosure;
[0012] FIG. **4** is a block diagram of an illustrative transceiver comprising a pair of first and second transceivers in accordance with some embodiments of the present disclosure;
[0013] FIG. **5** is a block diagram of an illustrative self-localizing apparatus in accordance with some embodiments of the present disclosure;
[0014] FIG. **6** is an illustrative timing diagram in accordance with some embodiments of the present disclosure;
[0015] FIG. **7** is a block diagram of an illustrative self-localizing apparatus comprising a pair of first and second first self-localizing apparatuses in accordance with some embodiments of the present disclosure;
[0016] FIG. **8** is a block diagram of an illustrative self-localizing apparatus comprising multiple selectable antennas in accordance with some embodiments of the present disclosure;
[0017] FIG. **9** is a block diagram of an illustrative localization unit, which includes a location update process, in accordance with some embodiments of the present disclosure;
[0018] FIG. **10** shows an illustrative mobile robot including a self-localizing apparatus in accordance with some embodiments of the present disclosure;
[0019] FIG. **11** is a block diagram of an illustrative control unit that may be used, for example, with the mobile robot of FIG. **10** in accordance with some embodiments of the present disclosure;
[0020] FIG. **12** shows an illustrative transceiver network with a large number of transceivers in accordance with some embodiments of the present disclosure;
[0021] FIG. **13** shows an illustrative simplified transceiver network in accordance with some embodiments of the present disclosure;
[0022] FIG. **14** shows an illustrative transceiver network having geographically adjacent cells in accordance with some embodiments of the present disclosure;
[0023] FIG. **15** shows an illustrative mobile robot operating in an area serviced by multiple transceiver cells in accordance with some embodiments of the present disclosure;
[0024] FIG. **16** shows illustrative input parameter maps that can be used for determining a schedule in accordance with some embodiments of the present disclosure;
[0025] FIG. **17** shows illustrative dynamic positioning performance map used for determining a schedule in accordance with some embodiments of the present disclosure;
[0026] FIG. **18** shows an illustrative example of how a schedule can be adjusted in accordance with

some embodiments of the present disclosure;

[0027] FIG. **19** shows another illustrative example of how a schedule can be adjusted in accordance with some embodiments of the present disclosure;

[0028] FIG. **20** shows an illustrative example of how a schedule can be adjusted for two groups of mobile robots in accordance with some embodiments of the present disclosure;

[0029] FIG. **21** is a diagram of an illustrative structure of a localization signal in accordance with some embodiments of the present disclosure;

[0030] FIG. **22** shows an illustrative transmission schedule that may be used to achieve a higher localization update rate in accordance with some embodiments of the present disclosure;

[0031] FIG. **23** shows a portion of the illustrative transmission schedule of FIG. **22** and corresponding receiver activity in accordance with some embodiments of the present disclosure;

[0032] FIG. **24** shows an illustrative transmission schedule of localization signals comprising two payloads in accordance with some embodiments of the present disclosure;

[0033] FIG. **25** shows an illustrative localization system and a corresponding performance map in accordance with some embodiments of the present disclosure;

[0034] FIG. **26** shows the illustrative localization system of FIG. **25** used with a different performance map in accordance with some embodiments of the present disclosure;

[0035] FIG. **27** shows the illustrative localization system and a corresponding performance map in accordance with some embodiments of the present disclosure;

[0036] FIG. **28** shows the illustrative localization system of FIG. **25** used with a different performance map in accordance with some embodiments of the present disclosure;

[0037] FIG. **29** shows an illustrative transmission schedule of localization signals in accordance with some embodiments of the present disclosure;

[0038] FIG. **30** shows another illustrative transmission schedule of localization signals in accordance with some embodiments of the present disclosure;

[0039] FIG. **31** shows an illustrative flow chart of logic that may be implemented on a self-localizing apparatus to configure its receiver in accordance with some embodiments of the present disclosure;

[0040] FIG. **32** shows an illustrative application of a performance map to an indoor and outdoor environment in accordance with some embodiments of the present disclosure;

[0041] FIG. **33** shows two illustrative localization networks in accordance with some embodiments of the present disclosure;

[0042] FIG. **34** is a block diagram of an illustrative bridge anchor in accordance with some embodiments of the present disclosure; and

[0043] FIG. **35** is a block diagram of another illustrative bridge anchor in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0044] In accordance with the present disclosure, limitations of current systems for localizing have been reduced or eliminated. In addition, the present disclosure provides various technical advantages over current localization systems.

[0045] Technical advantages of certain embodiments of the present disclosure relate to localizing objects in two-dimensional or three-dimensional space. For example, in an embodiment where a self-localizing apparatus is used to determine the location of a wheeled mobile robot, a transmission schedule may be optimized such that it accounts for the relative location of the anchors to the robot's operating area or current position, or such that it accounts for the robot's movement constraints (e.g., all possible locations are in a 2D plane). Further technical advantages of certain embodiments may optimize the performance of a localization system for a specific use case or application, either in real-time or offline. For example, in certain embodiments, the transmission schedule may be dynamically reconfigured based on predetermined rules (e.g., based on comparing the estimated location of a self-localizing apparatus with one or more predetermined

locations, based on a timecode, based on a property) or based on a request (e.g., an operator command).

[0046] Technical advantages of certain embodiments improve the localizing accuracy or precision. Technical advantages of certain embodiments improve the rate or latency at which the localizing information may be obtained or updated. For example, in certain embodiments overlapping yet not interfering localization signals may be used to allow a self-localizing apparatus to determine its position at a higher rate in a particular region or at a particular time. Technical advantages of certain embodiments improve the information content of the localization information. For example, in some embodiments a self-localizing apparatus may select to receive localization signals such that a particularly high uncertainty of its position estimate in a certain spatial direction or along a certain spatial axis is reduced.

[0047] Yet further technical advantages of certain embodiments relate to the reception of wireless signals used, for example, by a device to determine its own location. In some embodiments, the reception of localizing signals does not deteriorate when a direct line of sight cannot be established between a receiving device and a sufficiently large number of signal transmitters. For example, some embodiments allow operation in areas both without good line of sight to GNSS satellites and indoors. In some embodiments, signals are not distorted by multipath, do not suffer multipath fading observed in narrowband signals, or do not suffer from reduced signal quality when lacking direct line of sight in indoor environments. For example, some embodiments do not show performance degradation in enclosed environments (e.g., indoors), in forests, or in dense urban environments, such as those where retaining a lock on a GNSS signals becomes more difficult.

[0048] Technical advantages of some embodiments may allow arrival of a plurality of localization signals at a receiver's antenna with adequate time separation, avoiding degraded signal detection and reduced performance of a localization system, even in situations of signal overlap.

[0049] Technical advantages of some embodiments are such that they may be used in real-time or may be used by an unlimited number of receivers, to determine their 2D or 3D position, in GPS-denied environments or any environment where greater accuracy or system redundancy or failsafe operation may be desired.

[0050] Technical advantages of some embodiments may increase performance of current mobile robots and allow new uses of mobile robots by enabling localization with higher update rates, with lower latency, in larger spaces, or with higher accuracy than currently possible, resulting in more performant robot control.

[0051] Further technical advantages of some embodiments may allow a person, a mobile robot, or another machine to be equipped with a self-localizing apparatus that can determine its 3D position in space without the need to emit signals. This may increase localization performance and allow new uses of localization technology by providing regulatory advantages; by allowing scalability (e.g., the system may be used by an unlimited number of self-localizing apparatuses in parallel) or in an arbitrarily large space; by allowing higher redundancy (e.g., non-emitting apparatuses allow for more emitting anchors for a given network traffic load); by enabling more efficient bandwidth usage (e.g., lower emissions, less interference); by increasing energy efficiency of the receivers (e.g., by not requiring energy for transmissions); by enhancing privacy of operation; and by making data available locally where it is needed, resulting in increased update rates, lower latency, higher speed, and greater system robustness.

[0052] Further technical advantages of some embodiments may allow improved system performance by fusing data from several sources including one or more localization networks (e.g., UWB networks), readings of global properties from multiple locations, and onboard motion sensors.

[0053] Further technical advantages of some embodiments are linked to providing a distributed localization system. Such a system may provide increased robustness and safety for robot operation because it does not rely on sensor signals from a single source. It may also offer graceful

performance degradation by providing redundancy; may allow identification and resolution of inconsistencies in data by providing redundant data; and may provide higher performance by performing localization based on a comparison of the signals received from individual transceivers.

[0054] Yet further technical advantages of some embodiments allow for localization without direct line of sight between a transceiver and self-localizing apparatus. Moreover, further technical advantages allow for lower susceptibility to disturbance from radio frequency traffic, secure communications, and increasing resistance to interference, noise, and jamming.

[0055] Further technical advantages will be readily apparent to one skilled in the art from the following description, drawings, and claims. Moreover, while specific advantages have been enumerated above, various embodiments may include all, some, or none of the enumerated advantages. The listed advantages should not be considered as necessary for any embodiments.

[0056] The present disclosure uses timestampable signals (sometimes referred to herein as "localization signals"). Timestampable signals are radio frequency (RF) signals, with each signal having a feature that can be detected and that can be timestamped precisely. Examples of features include a signal peak, a signal's leading edge, and a signal preamble. Examples of timestampable signals include RF signals with a distinct, well-defined, and repeatable frequency increase or frequency decrease with time. Further examples of timestampable signals include signal bursts, signal chirps, or signal pulses. Further examples of timestampable signals include signals with features suitable for phase correlation or amplitude correlation techniques (e.g., signals with codes that have low auto-correlation values).

[0057] In some embodiments, the timestampable signal are "open-loop", one-directional RF signals transmitted over a reception area. Examples include DCF77 time code signals, GPS P-code signals, and terrestrial trunked radio signals. In some embodiments, the apparatus is a non-emitting apparatus.

[0058] In some embodiments, the timestampable signals use a narrow frequency band. In some embodiments, a center or carrier frequency in the ISM band is used. In some embodiments, a center or carrier frequency in the range of 1 to 48 GHz is used. In some embodiments, a center or carrier frequency in the range of 2.4 to 12 GHz is used. In some embodiments, a center or carrier frequency in the range of 3.1 to 10.6 GHz is used. In some embodiments, higher frequencies are used. Narrow band signals tend to suffer from multipath fading more than wide band signals (e.g., ultra-wideband (UWB) signals). In narrow band signals, signal duration is typically longer than the delay variance of the channel. Conversely, with UWB signals the signal duration is typically less than the delay variance of the channel. For example, in the case of an UWB system with a 2 nanosecond pulse duration, the pulse duration is clearly much less than the channel delay variation. Thus, signal components can be readily resolved and UWB signals are robust to multipath fading.

[0059] In some embodiments, the timestampable signals are UWB signals. UWB signals are spread over a large bandwidth. As used herein, UWB signals are signals that are spread over a bandwidth that exceeds the lesser of 125 MHz or 5% of the arithmetic center frequency. In some embodiments, UWB signals are signals that are spread over a bandwidth that exceeds the lesser of 250 MHz or 10% of the arithmetic center frequency. In some embodiments, UWB signals are signals that are spread over a bandwidth that exceeds the lesser of 375 MHz or 15% of the arithmetic center frequency. In some embodiments, UWB signals are signals that are spread over a bandwidth that exceeds the lesser of 500 MHz or 20% of the arithmetic center frequency. In some embodiments, a bandwidth in the range of 400-1200 MHz is used. In some embodiments, a bandwidth in the range of 10-5000 MHz is used. In some embodiments, a bandwidth in the range of 50-2000 MHz is used. In some embodiments, a bandwidth in the range of 80-1000 MHz is used. Ultra-wideband technology allows an initial radio frequency (RF) signal to be spread in the frequency domain, resulting in a signal with a wider bandwidth, ordinarily wider than the frequency content of the initial signal. UWB technology is suitable for use in a localization system because it can transmit very short-duration pulses that may be used to measure the signal's arrival

time very accurately and hence allow ranging applications. UWB signals may be advantageous for use in localization systems because of their capability to penetrate obstacles and to allow ranging for hundreds of meters while not interfering with conventional narrowband and carrier waves used in the same frequency bands.

[0060] In some embodiments, the arrival time of timestampable signals can be measured to within 0.6 nanoseconds relative to a clock. In some embodiments, the arrival time of timestampable signals can be measured to within 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, or 15 nanoseconds relative to a clock.

[0061] In some embodiments, the transmission rate is measured as the long time average of number of transmissions per second. In some other embodiments, the transmission rate is measured as the inverse of the long time average of the time separation between two subsequent transmissions. In some embodiments, the typical separation one of 1-500 microseconds, 1-1,000 microseconds, 1-500 milliseconds, 1-1,000 milliseconds, 1-5 seconds, 1-500 seconds, or any combination thereof. In some embodiments, no separation is used. In some embodiments, the longtime average is computed over a window of 1-10 seconds. In some other embodiments, the longtime average is computed over a window of 1-10 minutes. In some other embodiments, the longtime average is computed over a window of 10 minutes.

[0062] In some embodiments, the signal's mean equivalent isotropically radiated power (EIRP) density is smaller than −40 dBm/MHz at all frequencies. In some embodiments, the signal's mean EIRP density is smaller than −80, −70, −60, −50, −30, −20, or −10 dBm/MHz at all frequencies.

[0063] In some embodiments, the transmitted signal's maximum power is smaller than 0.1 mW per channel. In some embodiments, the transmitted signal's maximum power is smaller than 1.0 mW per channel. In some embodiments, the transmitted signal's maximum power is smaller than 100 mW per channel. In some embodiments, the transmitted signal's maximum power is smaller than 500 mW per channel. In some embodiments, the transmitted signal's maximum power is smaller than 10 W per channel.

[0064] In some embodiments, the less limiting of a signal's EIRP density and a signal's maximum power applies. In some embodiments, the more limiting of a signal's EIRP density and a signal's maximum power applies. In some embodiments, one of a limit on a signal's EIRP density and a limit on a signal's maximum power applies. In some embodiments, both of a limit on a signal's EIRP density and a limit on a signal's maximum power applies. In some embodiments, a limit applies to narrow band signal. In some embodiments, a limit applies to broadband signal.

[0065] In some embodiments, a transceiver's typical effective range is between 1 m and 50 m. In some embodiments, a transceiver's typical effective range is between 1 m and 100 m. In some embodiments, a transceiver's typical effective range is between 1 m and 500 m. In some embodiments, a transceiver's typical effective range is between 1 m and 1000 m. In some embodiments, a transceiver's typical effective range is between 1 m and 5000 m. In some embodiments, the apparatus may only receive UWB signals from a subset of transceivers.

[0066] In some embodiments, a maximum data rate of 50 Mbps is used. In some embodiments, a maximum data rate of 5 Mbps is used. In some embodiments, a maximum data rate of 1 Mbps is used.

[0067] In some embodiments, chirp spread spectrum (CSS) signals are used. In some embodiments, frequency-modulated continuous-wave (FMCW) signals are used.

[0068] Some embodiments include a localization unit. In some embodiments, the localization unit can compute at least one of (i) an orientation or orientation information, (ii) a position, or (iii) a motion of the self-localizing apparatus.

[0069] In some embodiments, the localization unit computes the location of the self-localizing apparatus based on the reception times of the timestampable signals and the known locations of the transceivers. In some embodiments, a time of arrival scheme is used. In some embodiments, a time difference of arrival scheme is used. Multilateration requires the localization unit to compute the

time-difference between the reception times of two timestampable signals. By subtracting the known time-difference of the signals' transmission times from the difference in their reception times (also referred to as a "TDOA measurement"), a localization unit may compute the difference in distance to the two transceivers, from which the signals were transmitted (e.g., transceiver two is 30 cm further away than transceiver one, since the reception of the signal from transceiver two was delayed by 1 ns in comparison to the signal from transceiver one). By computing the difference in distance between multiple transceivers, the localization unit may be able to compute the location of the self-localizing apparatus by solving a system of hyperbolic equations, or a linearized version thereof. Methods of solving this system of equations are well known to those skilled in the art and may include non-linear least squares, least squares, Newton iterations, gradient descent, etc. The method of multilateration requires the time-difference of the signals' transmission times to be known.

[0070] In some embodiments, the localization unit of the self-localizing apparatus may compute location iteratively. In some embodiments, rather than waiting for a timestampable signal to be received from all transceivers, the localization unit iteratively updates the location estimate whenever a signal is received. In some embodiments, when a timestampable signal is received, an adjustment to the current location estimate is computed based on the difference between its reception time and the reception time of a previously received timestampable signal. In some embodiments, a known method of filtering (e.g., Kalman filtering, particle filtering) is used to compute or apply this update. In some embodiments, the adjustment is computed based on the variance of the current location estimate (e.g., if the current estimate is highly accurate, less adjustment will be applied). In some embodiments, the adjustment is computed based on the locations of the two transceivers from which the timestampable signals were transmitted. In some embodiments, this adjustment is computed based on a measurement model, describing the probability distribution of a TDOA measurement based on the current location estimate and the locations of the two transceivers. In some embodiments, this enables more or less adjustment to be applied depending on how accurate the TDOA measurement is determined to be (e.g., if a first transceiver lies on a line connecting the current location estimate with a second transceiver, the TDOA measurement resulting from the two transceivers may be considered unreliable, and thus less adjustment applied).

[0071] In some embodiments, the localization unit updates a location estimate based on a system model, describing the probability distribution of the self-localizing apparatus' location. In some embodiments, this system model may be based on other estimated states (e.g., the velocity or heading of the self-localizing apparatus). In some embodiments, this system model may be based on input history (e.g., if an input command should yield a motion in the positive x-direction according to system dynamics, it is more probable the new location estimate lies in the positive x-direction, than in the negative x-direction).

[0072] In some embodiments, this system model may be based on measurements from a sensor or global property. In some embodiments, the localization unit may compute the location of the self-localizing apparatus based on a global property. In some embodiments, the localization unit may compute the location of the self-localizing apparatus based on the difference between a global property measured by the self-localizing apparatus and a global property measured by one or more of the transceivers (e.g., if both self-localizing apparatus and transceiver measure air pressure, the relative altitude difference between the two can be computed according to the known relationship between altitude and air pressure).

[0073] In some embodiments, the localization unit may use a history of location estimates and a system model to compute further dynamic states of the body, for example, velocity or heading. For example, if the history of location estimates indicates motion, velocity can be estimated. A further example is if the history of location estimates indicates motion in the positive y-direction, and the system model indicates that only forward motion is possible (e.g., a skid-steer car), the orientation

can be determined as oriented in the positive y-direction.

[0074] In some embodiments, the location is a ID location, a 2D location, a 3D location, or a **6**D location (i.e., including position and orientation).

[0075] In some embodiments, the performance of the localization unit (also referred to as localization performance or positioning performance) can be expressed as an average error of the position estimate. In some embodiments, the localization performance can be expressed as a variance of the position estimate. In some embodiments, the localization performance can be computed based on a dilution of precision. In some embodiments, the localization performance can be computed based on a latency (e.g., the time required for the location unit to detect a change of the self-localizing apparatus' position).

[0076] In some embodiments, the relative location computed by the localization unit is computed with an accuracy of 1 m, 20 cm, 10 cm, or 1 cm. In some embodiments, the time delay between the reception of timestampable signal and the computation of an updated position estimate provided by the localization unit is less than 50 ms, 25 ms, 10 ms, 5 ms, 2 ms, or 1 ms. In some embodiments, the system's update rate for full position updates or for partial position updates is more than 1 Hz, 5 Hz, 10 Hz, 50 Hz, 250 Hz, 400 Hz, 800 Hz, 1000 Hz, or 2000 Hz.

[0077] In some embodiments, a localization system comprises at least 1, 2, 3, 5, 7, 10, 25, 50, 100, or 250 anchors. In some embodiments, a localization system supports more than 1, 2, 3, 5, 10, 20, 40, 100, 200, 500, 1,000, 5,000, or 10,000 self-localizing apparatuses.

[0078] A clock as used herein refers to circuitry, structure, or a device that is capable of providing a measure of time. The measure of time may be in any suitable units of time. For example, the measure of time may be based on a base unit of a second. As another example, the measure of time may be based on a counter that increments at a particular rate. In some embodiments, the clock comprises an internal oscillator used to determine the measure of time. In some embodiments, the clock determines the measure of time based on a received signal (e.g., from an external oscillator). In some embodiments, a clock interface provides a clock signal.

[0079] In some embodiments, each transceiver may use its own onboard clock. In some embodiments, a single clock may generate a clock signal transmitted to each transceiver via cables or wirelessly. In some embodiments, the clock signal may be dependent on at least one-time code transmitted by a radio transmitter, or on at least one of a terrestrial radio clock signal, a GPS clock signal, and a time standard. In some embodiments, the clock signal may be based on a GPS-disciplined oscillator, on a transmitter, or on a time estimate computed from at least two clocks to improve accuracy or long-term stability of the clock signal.

[0080] Clocks may, for example, use a crystal oscillator or a temperature compensated crystal. In some embodiments, enhanced clock accuracy may be obtained through temperature stabilization via a crystal oven (OCXO) or via analog (TCXO) compensation or via digital/micro-controller (MCXO) compensation. In some embodiments, a centralized synchronization unit is used. In some embodiments, an atomic oscillator (e.g., rubidium) is used as a clock.

[0081] In some embodiments, a clock is configured to have an Allan variance of at most $(1\times10^{-8})^2$ or $(1\times10^{-9})^2$ or $(5\times10^{-10})^2$ for averaging intervals between 5 milliseconds and 10 milliseconds or for averaging intervals between 5 milliseconds and 100 milliseconds or for averaging intervals between 1 milliseconds and 1 second.

[0082] The apparatus or transceiver may be equipped with analog and digital reception electronics. The reception electronics may amplify the received signal and convert it to a base signal, which may then be demodulated and passed on to central processing electronics. An important design aspects of the receiver is to minimize noise and distortion. This may be achieved by carefully selecting reception electronics' components (especially those of the amplifier) and by optimizing the receiver's circuit design accordingly.

[0083] In some embodiments, the self-localizing apparatus is, or the self-localizing apparatus' antenna, analog reception electronics, and digital reception electronics are, configured to receive

two timestampable signals within a time window of 2, 10, or 50 seconds, wherein the time difference between the time stamps of the two UWB signals is within 0.6, 3, or 15 nanoseconds of the time difference between their actual reception times at the apparatus' antenna with reference to the apparatus' clock. The terms "receiver" and "reception electronics" used herein refer to the antenna, analog reception electronics, and the digital reception electronics that receive signals

[0084] In some embodiments, the apparatus' digital reception electronics are further operable to perform the timestamping of the received UWB signals with reference to the apparatus' clock in less than 1 millisecond, 100 microseconds, or 10 microseconds.

[0085] The apparatus or transceiver may be equipped with analog and digital transmission electronics.

[0086] In some embodiments, a transceiver is, or a transceiver's digital transmission electronics, analog transmission electronics, and antenna are, configured to transmit two timestampable signals within a time window of 2, 10, or 50 seconds, or configured such that the time difference between the transmission of two timestampable signals from the transceiver's antenna is within 0.6, 3, or 15 nanoseconds of the time difference between their scheduled transmission times with reference to the transceiver's clock. The terms "transmitter" and "transmission electronics" used herein refer to the antenna, analog transmission electronics, and the digital transmission electronics that are used to generate signals.

[0087] In some embodiments, a scheduling unit is used to schedule the signal transmission times. It will be apparent to one skilled in the art that any error by transceivers in adhering to this transmission schedule may affect the accuracy of the location computed by a localization unit.

[0088] In some embodiments, the scheduled time refers to the time at which the first pulse of the signal leaves the transceiver's antenna. In some embodiments, the scheduled time refers to the beginning of a start-of-frame delimiter (i.e., the point at which the transmitted signal changes from the repeated transmission of a preamble code to the transmission of the start-of-frame delimiter). In some embodiments, the apparatus is configured to compare two timestampable signals transmitted by the same transceiver.

[0089] In some embodiments, transceivers coordinate their transmissions at the packet level. In some embodiments, signal overlap is avoided. In some embodiments, signals are transmitted in a round-robin fashion; at regular intervals; in a specific time sequence; or taking turns. In some embodiments, transceivers transmit signals simultaneously. In some embodiments, transceivers transmit signals that partially overlap.

[0090] In some embodiments, each of three or more transceivers includes a scheduling unit. In some embodiments, a single scheduling unit is operationally coupled to three or more transceivers. In some embodiments, this operational coupling is a wired connection. In some embodiments, this operational coupling is a wireless connection. In some embodiments, this wireless operational coupling is implemented using signals such as UWB signals. In some embodiments, the scheduling unit uses a lower update rate than the localization signal rate.

[0091] In some embodiments, the scheduling unit is operable to ensure a time separation of at least 5 microseconds, 10 microseconds, or 50 microseconds between one transceiver terminating its transmission and a different transceiver beginning its transmission. In some embodiments, the scheduling unit is operable to monitor the localization signals. In some embodiments, the scheduling unit is operable to compute an improved scheduling. In some embodiments, the scheduling unit is operable to ensure a time separation of at least 1 microsecond, 5 microseconds, or 10 microseconds between the end of one signal and the start of a second signal emitted by the same transceiver. In some embodiments, the scheduling unit is operable to maintain a memory of the assignment of media access control addresses and scheduled transmission times.

[0092] In some embodiments, each of the three or more transceivers comprises a sensor. In some embodiments, the sensor is physically and operationally coupled to the transceiver. In some embodiments, the sensor is operable to provide data representative of the orientation, the position,

or the movement of the transceiver. In some embodiments, the sensor is structured to detect a disturbance to the transceiver's position or orientation. In some embodiments, the sensor signal is a signal of a sensor physically connected to a transmitter, wherein the sensor signal is transmitted as part of a payload of a signal, such as an UWB localization signal.

[0093] In some embodiments, the self-localizing apparatus comprises a sensor, physically and operationally coupled to the apparatus and operable to provide data representative of the orientation of the apparatus. In some embodiments, the sensor is operable to provide data representative of the orientation, the position, or the movement of the apparatus. In some embodiments, the sensor is configured to provide data representative of the orientation of a self-localizing apparatus' antenna.

[0094] Data from a sensor may be processed by a localization unit or by a position calibration unit. For example, data related to a landmark may be compared with other data (e.g., data related to another landmark, data from memory, sensor data, data representative of a location) to improve a position estimate or a position calibration unit. As another example, a comparison of the position of a landmark relative to a transceiver detected by a first camera and the position of the same landmark relative to a self-localizing apparatus detected by a second camera may allow a localization unit to improve a localization estimate. A comparison may use data related to one or more landmarks. A comparison may use data related to observations by one or more visual sensors.

[0095] Typical examples of sensors that may be usefully employed as part of the present disclosure include an optical sensor, an accelerometer, a magnetometer, and a gyroscope.

[0096] In some embodiments, micro-electro-mechanical systems (MEMS) or piezoelectric systems may be used to allow achieving operating characteristics outlined in the present disclosure. Examples of such micro-sensors that can be usefully employed with the present disclosure include MEMS gyroscopes, MEMS accelerometers, piezoelectric gyroscopes, and piezoelectric accelerometers. In some embodiments, the use of micro-sensors allows using one or more inertial measurement units (IMUs), which may each combine multiple gyroscopes or accelerometers or use multiple-axis gyroscopes or accelerometers, in each subsystem. In some embodiments, such selection of micro-sensors allows creating or using a self-localizing apparatus suitable for highly dynamic movement that require low weight and low power consumption in spite of high performance. For example, a 3-axis MEMS gyroscope may be used to monitor a self-localizing apparatus' attitude and to allow triggering a signal if an attitude threshold is exceeded. As another example, a MEMS gyroscope may be used to control a small flying robot equipped with a self-localizing apparatus around hover in spite of its low time constant. Examples of optical sensors include infrared sensors, linear cameras, optic flow sensors, and imaging sensors, among others.

[0097] Some embodiments comprise a global property sensor, i.e., a sensor operable to provide data representative of a global property.

[0098] Examples of global properties include fields that have a determinable value at multiple or every point in a region, such as a gravitational force, an electromagnetic force, a fluid pressure, and a gas pressure. Further examples of global properties include an RF signal strength, a GPS signal, the Earth's magnetic field, the Earth's gravitational field, the atmosphere's pressure, landmarks, and radio time signals (e.g., those sent by DCF77 time code transmitters). Examples of landmarks include the horizon, the sun, moon or stars, mountains, buildings, and prominent environmental features. Prominent environmental features may include distinctive natural features such as mountains, distinctive buildings such as monuments, and others such as those used in simultaneous localization and mapping (SLAM). Further examples for landmarks include those used in Scale-Invariant Feature Transform (SIFT) and Speeded Up Robust Features (SURF). Note that in the present disclosure, GPS or GNSS may be used as a placeholder to describe any similar signals by other global navigation satellite systems such as e.g., GLONASS, Galileo, IRNSS, or BeiDou-2 as well as their improved versions such as real-time kinematic (RTK) GPS or DGPS.

[0099] In some embodiments, an apparatus and a transceiver are both configured to detect the same global property. In some embodiments, a transceiver is configured to communicate data

representative of the global property at its location to an apparatus or to another transceiver, and the apparatus or the another transceiver is configured to compare the data with data representative of the same global property at the apparatus' or the another transceiver's location. In some embodiments, the global property can be associated with a global property model.

[0100] In some embodiments, the global property sensor is an orientation sensor. The orientation sensor may enable the transceiver to measure its orientation relative to a frame of reference common to the transceivers and the self-localizing apparatus. The transceiver may then transmit signals representative of its orientation included as data (payload) within the localization signals. In some embodiments, a transceiver is capable of measuring its orientation and of transmitting this orientation as a payload of a localization signal.

[0101] In some embodiments, a position calibration unit may compute an estimate for the position of a transceiver. In some embodiments, the transceiver position is computed once (e.g., as part of a calibration routine during the localization system's setup). In some embodiments, the transceiver position is computed continuously (e.g., each time new data related to the transceiver's position becomes available). In some embodiments, the transceiver position unit is initialized with known, partially known, estimated, or partially estimated position information (e.g., initial transceiver distances, positions, or orientations may be measured or entered manually).

[0102] Position calibration may be achieved in various ways. For example, the position calibration unit may compute a transceiver's position based on time stamped signals received from other transceivers with known locations. This may, for example, allow for the addition of an additional transceiver to an existing network of transceivers. In some embodiments, a position calibration unit operates analogously to a localization unit or vice versa. In some embodiments, a position calibration unit is operationally coupled to a compensation unit.

[0103] In some embodiments, a single position calibration unit may be used to compute the location of multiple transceivers relative to each other. This may, for example, allow initialization of a network of transceivers that do not yet have known locations. In some embodiments, multiple position calibration units are used (e.g., one for each transceiver).

[0104] In some embodiments, a position calibration unit is implemented offboard a transceiver. For example, the position calibration unit may be implemented on a laptop computer connected to the transceiver using a cable. This may, for example, allow for a more convenient interface for an operator.

[0105] In some embodiments, the synchronization unit is operable to synchronize at least one of (i) an offset of the first clock, and (ii) a rate of a first clock, based on a second clock. In some embodiments, the correction is computed or the synchronization is performed based on at least one of an average, a median, and a statistical property of a multitude of the localization system's clocks. In some embodiments, global properties that also provide timing information, such as those provided by GPS, DCF77, and further systems, are used. In some embodiments, the synchronization unit uses global properties that also provide timing information.

[0106] In some embodiments, the synchronization unit is operable to implicitly or explicitly account for timing errors introduced by at least one of (i) a first difference between the rate of the apparatus' clock and the rate of a first communicating transceiver's clock and (ii) a second difference between the rate of the apparatus' clock and the rate of a second, different communicating transceiver's clock.

[0107] In some embodiments, the synchronization unit is operable to perform the synchronization or to compute the clock correction based on a compensation computed by a compensation unit or data stored in a memory.

[0108] In some embodiments, the synchronization unit is operable to synchronize the onboard clock's rate such that the statistical mean error between the onboard clock's rate and the median of the two other transceivers' onboard clock rates is less 10 parts per million or 1 part per million or 100 parts per billion. In some embodiments, the synchronization unit is operable to synchronize the

onboard clock's offset such that the statistical mean error between the onboard clock's offset and the median of the two other transceivers' onboard clock offsets is less than 10 nanoseconds or 5 nanoseconds or 1 nanosecond or 10 picoseconds. In some embodiments, this is achieved by implicitly or explicitly accounting for timing errors introduced by one or more of the transceiver's antenna, and the transceiver's analog and digital transmission electronics, or by computing clock corrections to the onboard clock's offset based on the timestamped UWB clock synchronization signal and data provided by the transceiver's memory unit, or by altering a clock rate (e.g., but altering a voltage, a temperature, or a crystal trim of a clock).

[0109] In some embodiments, a compensation unit is used to correct for signal delays. The compensation unit computes compensations for effects on the timestampable signal from the moment of scheduling the transmission time of the signal at the transceiver to the moment of timestamping the signal at the transceiver's or apparatus' reception electronics.

[0110] Compensation is typically achieved by correcting the reception time stamp or by correcting transmission time information (e.g., a transmission time stamp included in the UWB data as payload), e.g. based on signal quality or group delay. This correction may be computed and applied immediately (e.g., by computing corrections for or modifying individual timestamps) or in batch (e.g., by computing corrections for or modifying timestamps in batch). The compensation may use several data sources to determine the required correction; examples include (i) data representative of the location and orientation of the transceivers and the apparatus; (ii) data provided by onboard sensors; (iii) data stored in a memory; (iv) data provided by the synchronization unit; and (v) quality metrics provided by the digital reception electronics.

[0111] In some embodiments, the compensation unit compensates for effects of position, orientation, or movement of the apparatus' antenna relative to a transceiver's antenna. In some embodiments, the compensation unit compensates for effects of obstacles. In some embodiments, the compensation is performed by computing (i) data representative of a correction for a distance, time, or duration, (ii) data representative of a correction for a comparison of a first and a second distance, time, or duration, or (iii) data representative of a correction for a comparison of a multitude of distances, times, or durations. In some embodiments, the data representative of a correction is provided to the localization unit.

[0112] In some embodiments, the compensation unit may also account for the impact of the relative orientation, direction and distance of the apparatus' antenna relative to the transceiver's antenna. This is important due to the difficulty in creating omnidirectional antennae for timestampable signals such as UWB signals. This is also important because some apparatuses may be receiving signals from a larger number of transceivers, receiving signals at a higher update rate, or receiving signals with a higher quality than others, depending on their location in space relative to the transceivers, or on the communication architecture used. Corresponding data related to the computation of compensation values may be determined as part of a calibration routine or during use (e.g., provided by an operator), and improved using assumptions (e.g., radial symmetries) or using data from other system components as outlined above. They may then be stored in a memory for use, e.g. as a look-up table of compensation values for different pairwise combinations of relative antenna orientations, directions, and distances.

[0113] Strategies similar to those outlined above for the compensation unit and timestampable signals may also be used by the synchronization unit or for clock synchronization signals.

[0114] It will be understood that while compensation and various aspects thereof are sometimes explained for signals travelling between an apparatus and a transceiver, explanations may be equally valid, and analogously used, for signals travelling between two apparatuses or two transceivers.

[0115] A control unit is used to generate control signals for actuators based on data received from a localization unit (e.g., a position estimate) or of sensors (e.g., an onboard sensor) or of a global property (e.g., an atmospheric pressure).

[0116] The control unit can implement control laws that are well-established in the prior art or widely used. Examples of such control laws include PID control; model predictive control; sliding mode control; full state feedback; and backstepping control. Depending on the control law, the control unit may use state estimates provided by a localization unit.

[0117] A control unit may compute control signals for a single actuator. In some embodiments, a control unit computes different sets of control signals for different sets of actuators. For example, a control unit may compute a first set of control signals for two actuators of a first module or axis of a robot and a second set of control signals for a second module or axis of a robot.

[0118] Actuators may belong to the group of electric, magnetic, and mechanical motors moving or controlling a mechanism or system. Examples include a piezoelectric actuator, a brushless electric motor, and a servo motor.

[0119] In some embodiments, the apparatus' actuator is configured to move the apparatus in its three translational degrees of freedom. In some embodiments, the actuator is configured to move the apparatus in its three rotational degrees of freedom. In some embodiments, the actuator is configured to move a part of the apparatus, such as the antenna. In some embodiments, multiple actuators are used in conjunction.

[0120] In some embodiments, the apparatus' actuator is configured to move the apparatus' position by at least 30 cm. In some embodiments, the apparatus' actuator is configured to move the apparatus' position by at least 100 cm. In some embodiments, the apparatus' actuator is configured to move the apparatus' rotation by at least 30 degrees. In some embodiments, the apparatus' actuator is configured to move the apparatus' rotation by at least 90 degrees.

[0121] FIG. **1** is a block diagram of an illustrative localization system **100** (sometimes referred to herein as a "network") that includes components involved in the generation and execution of a schedule for transmitting localization signals in accordance with some embodiments of the present disclosure. System **100** comprises scheduler **110**, scheduling unit controller **120**, and transceivers **130** (also referred to herein as an "anchor").

[0122] Scheduler **110** uses one or more input parameters to determine the schedule. As illustrated, the input parameters may comprise one or more user requirements, anchor locations, and anchor properties. The user requirements may include desired positioning performance. For example, a user may specify a minimum positioning performance within a localization region. As another example, a user may specify different positioning performance within the localization region. In some embodiments, the positioning performance may be input via a two- or three-dimensional map, where zones within the localization region are marked with the desired positioning performance. The anchor locations may be input according to a known coordinate system. In some embodiments, a user may input the anchor locations. In some embodiments, the localization system **100** may be configured to determine the locations of the anchors using the localization signals. The anchor properties may include the connectivity of the anchors to each other and other anchor properties such as the available configurations (e.g., whether an anchor can receive and transmit at the same time), the frequencies to which the anchor can be set, antenna radiation pattern, any other suitable anchor properties, and any combination thereof.

[0123] Scheduler **110** may include one or more inputs such as a user input or a communication input for receiving the input parameters. The user input may include, for example, a keyboard, a mouse, a touch screen, buttons, switches, a touch pad, or any other suitable user input device. The communication input may include, for example, a wired interface (e.g., using USB, RS-232, Ethernet, or other standards) or a wireless interface (e.g., using Wi-Fi, IR, WiMAX, wireless BLUETOOTH, or other standards). Scheduler **110** may also include a processor and memory. The processor may be adapted to execute computer program instructions stored in the memory, which may include an operating system and one or more applications, as part of performing the functions described herein. For example, the processor may be configured to receive the one or more input parameters, process the one or more inputs, and determine an appropriate schedule as explained in

more detail below. Scheduler **110** may also include an output for outputting the schedule to the anchors, such as transceivers **130**. In some embodiments, the schedule is first outputted to scheduling unit controller **120**. The output may, for example, include a wired interface or a wireless interface. In some embodiments, the output may be the same as the communication input. In some embodiments, scheduler **110** may be implemented as a personal computer.

[0124] Scheduling unit controller **120** facilitates the transmission of the schedule to the anchors. In some embodiments, scheduling unit controller **120** may be in communication with one or more anchors such as transceivers **130**. In some embodiments, scheduling unit controller **120** may process the schedule received from scheduler **110**. For example, scheduling unit controller **120** may prepare the schedule for transmission to the anchors. In one embodiment, the processing comprises translating the schedule and preparing it for transmission to the anchors. This may involve parsing a schedule file format (e.g., a XML or YAML file), converting the data in the file into a scheduling unit-specific format, adding information such as a unique schedule ID, serializing the data, and adding data protection information such as a CRC. Scheduling unit controller **120** may transmit the schedule (e.g., in its translated format) to the anchors such as transceivers **130**. In some embodiments, the transmission is performed using the same type of wireless signals that are normally used for localization purposes. In this case, scheduling unit controller **120** comprises digital transmission electronics, analog transmission electronics, and an antenna. These components are described in more detail below. In some embodiments, the transmission is performed through a wired interface or a separate wireless transmission channel that is available to both scheduling unit controller **120** and the anchors.

[0125] Scheduling unit controller **120** is shown as a separate component in localization system **100**. However, it will be understood that this is merely illustrative. In some embodiments, scheduling unit controller **120** or the functionality of scheduling unit controller **120** may be integrated into other components. For example, scheduling unit controller **120** may be integrated into scheduler **110**. As another example, scheduling unit controller **120** may be integrated into one or more anchors such as transceivers **130**.

[0126] As mentioned above, localization system **100** may include transceivers **130**. Transceivers **130** are configured to receive a schedule from scheduling unit controller **120**. Each transceiver **130** may receive the schedule directly from scheduling unit controller **120** or indirectly through one or more other transceivers. The received schedule may be stored in a memory within each transceiver, from where it may be accessed by a scheduling unit of each transceiver. The details of transceivers **130** are described below.

[0127] In some embodiments, transceivers **130** are capable of switching between different schedules. This may be achieved by including several scheduling units within each transceiver, or by using a single scheduling unit which is configured to receive a signal that will cause the scheduling unit to switch to a different schedule. Several schedules may be received from scheduling unit controller **120**, including for example, unique identifiers that allow a scheduling unit to determine which schedule to use depending on a received signal. In some embodiments, the received signal could cause the scheduling unit to interrupt the current schedule, to restart the current schedule, or to jump to a specific point in the schedule. In some embodiments, the first part of a long schedule may be designed to facilitate the clock synchronization between the network transceivers while the second part may be designed to optimize the localization performance. The scheduling unit controller may send a signal to restart the execution of the schedule when the network synchronization error increases above a certain threshold. In some other embodiments, the execution of the schedule may have to be restarted from the beginning or from a certain point in time every time a self-localizing apparatus enters the region of space covered by the network of transceivers. In some embodiments, the point in time from which the execution of the schedule is restarted may depend on the position from which the self-localizing apparatus enters the region of space. In some embodiments, a default schedule (e.g., one based on the ALOHA protocol) may be

permanently stored in a memory of a transceiver, and an additional schedule can be transmitted by scheduling unit controller **120**. A transceiver could then operate in a default mode (based on the default schedule) or an improved-performance mode (e.g., based on an optimized schedule received from scheduling unit controller **120**).

[0128] FIG. **2** is a block diagram of three illustrative transceivers **130** and two self-localizing apparatuses **140** of an illustrative localization system **100** in accordance with some embodiments of the present disclosure. In some embodiments, localization system **100** of FIG. **2** is the same as localization system **100** of FIG. **1**. In some embodiments, localization system **100** of FIG. **2** is a different localization system than that depicted in FIG. **1**. Each of the three transceivers **130** transmits timestampable localization signals **202**. In some embodiments, the three stationary transceivers **130** have known relative locations to each other. In some embodiments, the three transceivers **130** have synchronized clocks **210**. Transceivers are sometimes referred to herein as "anchors" or "beacons". It will be understood that while three transceivers and two self-localizing apparatuses are illustrated in FIG. **2**, any suitable numbers of transceivers and self-localizing apparatuses may be used in localization system **100**.

[0129] Each transceiver **130** in FIG. **2** comprises analog electronic components **214** and digital electronic components **216**. An antenna **212** is coupled to analog transmission electronics **214**. Analog transmission electronics **214** may generate an analog transmission signal from at least one digital data packet. Digital data packets are provided by digital transmission electronics **216**. The analog transmission signal can be generated using an analog pulse generator. The analog transmission signal may also be amplified by an amplifier before being passed to antenna **212** for transmission.

[0130] In FIG. **2**, transmission electronics **214**, **216** are used to convert payload data (sometimes called "payload") into signals **202** that may then be transmitted by transmitters **130**. In some embodiments, signal **202** is an UWB signal. A single UWB signal **202** transmitted by a single transceiver **130** can be received by a plurality of apparatuses **140**. Each apparatus may use information gained from multiple signals **202** to compute its location without emitting signals of its own.

[0131] Clock **210** is coupled to transmission electronics **214**, **216** and provides timing information for transmitting signals **202**. Clock **210** may include an onboard clock or may have a wireless or wired connection (not shown) that receives time information from an offboard clock (not shown), e.g., at a remote location.

[0132] Transmissions (e.g., signals **202**) from three transceivers **130** may be coordinated using a scheduling unit **218**, which is operable to schedule the transmission of signals **202**. In some embodiments, scheduling unit **218** may provide sufficient time separation between the localization signals to prevent transceiver messages from arriving at a receiver's antenna without adequate time separation, which can result in degraded signal detection and hence reduced performance of localization system **100**. In some embodiments, scheduling unit **218** may implement an ALOHA protocol to reduce or prevent the effect of insufficient time separation. In some embodiments, signal transmission may follow a pre-programmed schedule, or scheduling may be performed centrally and a schedule communicated to each transceiver as described, for example, in FIG. **1**. In some embodiments, scheduling may be performed by each transceiver. For example, the scheduling for a transceiver may be based on information stored by the transceiver about the other transceivers (e.g., an ordered list or a transmission schedule of the other transceivers in range). In some embodiments, the scheduling unit may furthermore provide configuration signals to the transmission electronics. These configuration signals can be interpreted by the transmission electronics to adjust certain settings of the transmitter, for example, the center frequency, the signal bandwidth, the preamble code, the preamble length, transmission power, or antenna.

[0133] Analog transmission electronics **214** are coupled to digital transmission electronics **216** and together they allow the transmission of UWB signals **202**. Such transmissions may be performed

such that the transmission of signal **202** from antenna **212** occurs accurately at a specified transmission time relative to clock **210**. This can be achieved using digital transmission electronics **216**. Digital transmission electronics **216** may coordinate its operation with scheduling unit **218**. The transmission of a signal at a specified time is preferably performed such that a specific symbol is emitted from the antenna **212** at the specified time. For transmissions that follow the IEEE 802.15.4 standard, a common choice for the symbol to be transmitted at that time is the beginning of the start-of-frame delimiter, i.e., the point at which the transmitted signal changes from the repeated transmission of the preamble code to the transmission of the start-of-frame delimiter. Digital transmission electronics **216** may use the signal provided by clock **210** as a reference in this transmission at the specified time; the transmission time can therefore be expressed relative to this clock.

[0134] The two self-localizing apparatuses **140** shown in FIG. **2** are each configured to receive the UWB radio signals **202** transmitted by transceivers **130**.

[0135] FIG. **3** is a detailed block diagram of illustrative transceivers **130** in accordance with some embodiments of the present disclosure. In some embodiments, transceivers **130** of FIG. **3** are used in localization system **100** of FIG. **1** or localization system **100** of FIG. **2**. In some embodiments, transceivers **130** of FIG. **3** are used with a different localization system than that depicted in FIGS. **1** and **2**.

[0136] Transceivers **130** of FIG. **3** may each include an antenna **212** that is coupled to both analog transmission electronics **214** and analog reception electronics **220**. In some embodiments, a TX/RX-switch is used to connect the antenna to one or the other of electronics **214**, **220**. Analog reception electronics **220** is coupled to digital reception electronics **222** and together they allow the reception of signals **302** transmitted by other transceivers **130**. Analog and digital reception electronics **220**, **222** may have similar capabilities to the ones on self-localizing apparatus **130** of FIG. **2**. For example, analog and digital reception electronics **220**, **222** may convert signals **302** into data (the payload), accurately determine the time at which the transmitted signal reached antenna **212**, and may provide additional quality metrics related to received signal **302** such as signal strength, reception time standard deviation, and metrics for determining whether the signal travelled in line of sight or not, among others.

[0137] Digital reception electronics **222** are operationally coupled to a synchronization unit **224**, which may be used to identify and compensate for a clock **210** of any one transceiver not running in perfect synchrony with the clocks of the other transceivers. Upon reception of an UWB radio signal, the received data, timestamp, and quality metrics are sent to synchronization unit **224**. Synchronization unit **224** may compare the reception time stamp to previous reception time stamps, to transmission time information included in the data (payload) of the signal, and to transmission time information included in previous signals **202**. From this information, synchronization unit **224** may compute the current behavior of clock **210** such as, for example, its current clock rate, or the current rate of change of the clock rate. In addition, synchronization unit **224** may determine the time-of-flight of signals between stationary transceivers by evaluating the discrepancy between locally measured reception timestamps, locally set transmission times, measured reception timestamps reported from other transceivers, and set transmission times of other transceivers. Through careful correction for errors such as differing clock offsets, clock rates, and signal propagation times, synchronization unit **224** may compute a correction to allow the transceivers to obtain a common, synchronized reference time. In some embodiments, synchronization uses signals **302** received from other transceivers **130**. Time synchronization between the transceivers is beneficial, for example, because any offset in transceiver timing may translate into errors in the localization of the self-localizing apparatus.

[0138] Transceiver **130** of FIG. **3** may also include a sensor **226** and a global property sensor **228**. Both of these sensors are coupled to digital transmission electronics **216**. This enables signals representative of the measurements taken by sensor **226** and global property sensor **228** to be

included in the data that is transmitted by digital transmission electronics **216**, analog transmission electronics **214**, and antenna **212** in the form of localization signals **202**.

[0139] In some embodiments, a sensor **226** or a global property sensor **228** may be used to sense a transceiver's orientation. With knowledge of the transceiver's orientation, a self-localizing apparatus (e.g., self-localizing apparatus **140** of FIG. **2**) that receives a localization signal from that transceiver may be able to compensate for signal delays introduced by the relative orientation of the transceiver's antenna **212** to the self-localizing apparatus' antenna. This may, for example, be achieved by communicating the transceiver's detected orientation as part of its transmitted localization signal.

[0140] Each transceiver **130** may be equipped with memory **230**, which may be used to store data such as configuration data, desired signal amplification, synchronization data (e.g., offsets or rate corrections for clocks), or range accuracy calibration data. Memory **230** may also be used to buffer data after reception and before transmission. In some embodiments, memory **230** can be rewritten multiple times or is non-volatile memory. In some embodiments, memory **230** is used to store one or more transmission schedules.

[0141] FIG. **3** shows illustrative transceivers that can receive and process wireless signals from other transceivers (sometimes referred to herein as "wireless transceivers" or "wireless UWB transceivers"). This is enabled by transceivers **130** having analog reception electronics **220** and digital reception electronics **222**, which are operable to receive signals transmitted by other transceivers **130**.

[0142] A first transceiver **130** may use one or more signals **302** from a second transceiver **130** or from a plurality of other transceivers **130** to adjust its transmission schedule to, e.g., provide better time separation between transmissions. This may, e.g., be achieved by scheduling unit **218** storing in a memory **230** the times at which signals **302** were received from other transceivers **130** in the network (e.g., network **100** of FIG. **2**), and subsequently adjusting the local transmission schedule based on these times. In some embodiments, better time separation between transmissions results in reduced interference between localization signals **202** and signals **302**. In some embodiments, measurement of the time separation between localization signals **202** may be a metric used for assessing or when improving the performance of a localization network.

[0143] In some embodiments, signals **302** may be used by a transceiver **130** to indicate the occurrence of an event. In some embodiments, signals **302** may be used by a transceiver **130** to trigger an action by other transceivers **130**. In some embodiments, the action results in the scheduling of localization signals **202** or in a change of a transmission schedule. In some embodiments, dynamic transmission scheduling may be used to react to the addition or removal of transceivers from the system. In some embodiments, the reaction of the localization network (e.g., network **100** of FIG. **2**) to the addition or removal (e.g., due to a fault) of transceivers may be used as a metric to assess the robustness of the network.

[0144] In some embodiments, signals **302** may be the same type of signals used by self-localizing apparatuses (e.g., signals **202**). In some embodiments, signals **302** may be in some way different from signals **202**. For example, signals **302** may have a different payload. In some embodiments, signals **302** may be transmitted at different times than signals **202**. For example, signals **302** may be transmitted during installation or during a calibration phase of a localization system, and signals **202** may be emitted when the system is in operation. Signals **302** and **202** may also differ in further ways (e.g., their signal strength, preamble, etc.). In some embodiments, the use of signals **202** and signals **302** may differ. For example, transceivers may emit signals **202** at a different update rate from that used with signals **302**, or the signal emission may follow a different schedule.

[0145] FIG. **4** is a block diagram of an illustrative transceiver comprising a pair of first and second transceivers **130***a*, **103***b* in accordance with some embodiments of the present disclosure. Transceivers **130***a*, **130***b* are physically coupled together using a structural element **400**. Each transceiver **130***a*, **130***b* comprises an antenna **212***a*, **212***b*, analog transmission electronics **214***a*,

214*b*, digital transmission electronics **216***a*, **216***b*, and a clock interface **402***a*, **402***b*. First transceiver **130***a* may also comprise a global property sensor **228**, which may be operationally coupled to the digital transmission electronics **216***a*.

[0146] For many applications, transceivers will have fewer constraints (e.g., weight constraints, size constraints, power constraints) than self-localizing apparatuses, because transceivers do not have to be mobile. It may therefore be preferable to shift complexity away from self-localizing apparatuses towards transceivers. The embodiment shown in FIG. **4** has several technical advantages. First, the pair of transceivers shown in FIG. **4** may be implemented as redundant receivers to provide an additional safeguard against failure. Depending on the use case, redundancy can be achieved for some or all of the transceiver's components. Second, transceivers **130***a*, **130***b* may be configured as illustrated to use different antennas **212***a*, **212***b* to provide additional functionality. Antennas **212***a*, **212***b* may, for example, differ in their orientation, in their antenna polarization, or in their gains, among other factors. This may result in technical advantages for a receiver, including an improved signal-to-noise ratio or less variation in signal reception across different receiver antenna orientations. In some embodiments, transceivers **130** of FIGS. **1-3** may use multiple antennas **212**, e.g., connected with an RF switch.

[0147] Using a pair of transceivers as shown in FIG. **4** may have additional advantages when used with similarly paired self-localizing apparatus (e.g., as shown in FIG. **7**). In some embodiments, transceivers **130***a* and **130***b* may use different localization signals. For example, transceiver **130***a* may use a first frequency band while transceiver **130***b* may use a second, different frequency band. The simultaneous use of two different localization signals may allow higher update rates. It may provide improved resistance to interference. It may also allow disambiguation of signal-dependent effects from true differences in distance. For example, because a signal's speed depends on the refractive index of an obstacle and on the signal's wavelength, the use of two different signals with two different wavelengths may allow the delay introduced by the obstacle to be inferred.

[0148] Paired embodiments may also be used to detect a failure. This may, for example, be achieved by receiving a first signal from a first transceiver; receiving a second signal from a second transceiver that is physically attached to the first transceiver; comparing data related to the first signal with data related to the second signal while accounting for a difference in the two signals; and comparing the result to a threshold. Examples of the compared data include the reception of a signal; the accuracy of a signal's arrival; and the peak power of a signal. Examples for the difference in the two signals include a relative antenna position; a time delay between emission of the first and second signal; and a signal preamble.

[0149] In some embodiments, a failure is detected using a failure detection unit (not shown). In some embodiments, a failure detection unit is onboard the self-localizing apparatus. In some embodiments, a failure detection unit is offboard the self-localizing apparatus. In some embodiments, a single failure detection unit is used.

[0150] In some embodiments, paired antennas may be used to implement a multi-antenna setup.

[0151] The transceiver shown in FIG. **4** further comprises digital reception electronics **222***a*, **222***b* and analog reception electronics **220***a*, **220***b*. This allows each of transceivers **130***a*, **130***b* to exchange signals **302** wirelessly. In some embodiments, transceivers **130***a*, **130***b* do not include some or all of electronics **222***a*, **222***b*, **220***a*, **220***b*.

[0152] In some embodiments, the transceivers of the present disclosure may be used with a multi-antenna setup. A multi-antenna setup comprises at least two resonant elements (sometimes called "antennas") with known diversity (e.g., spatial diversity, time diversity, polarization diversity, pattern diversity, etc.).

[0153] A multi-antenna setup's resonant elements may differ in one or more of their characteristics (e.g., polarity, frequency response, sensitivity, orientation, etc.). For example, antennas may be separated by a known distance. As another example, antennas may be oriented orthogonally with respect to each other. The resonant elements of a multi-antenna setup may be used and combined in

various ways using well-known radio frequency techniques (e.g., diplexers, power dividers, etc.). A multi-antenna setup may comprise dedicated electronics for an individual resonant element.

[0154] In some embodiments, a transceiver's antennas **212***a*, **212***b* may be used to implement a multi antenna setup. A multi antenna setup may comprise some separate electronics **214***a*, **214***b*, **216***a*, **216***b*, **220***a*, **220***b*, **222***a*, or **222***b* for an individual resonant element. For example, a multi-antenna setup may comprise separate reception electronics for an antenna.

[0155] In some embodiments, a transceiver is equipped with multiple antennas. In some embodiments, a transceiver's multiple antennas are used to implement a multi-antenna setup. In some embodiments, a self-localizing apparatus is equipped with multiple antennas. In some embodiments, a self-localizing apparatus' multiple antennas are used to implement a multi-antenna setup. In some embodiments, a transceiver and a self-localizing apparatus each have a multi-antenna setup.

[0156] In some embodiments, identical antennas are used for transmission and reception. In some embodiments, different antennas are used for transmission and reception. For example, transmitters may use a directional antenna while self-localizing apparatuses use omnidirectional antennas, or vice-versa. Various types of antennas may be used and combined to achieve the desired behavior for a given use case. For example, antennas using multiple resonant elements, Multi-Beam Adaptive Antennas, or Multiple-Input Multiple-Output Antennas (MIMO) may be used. In some embodiments, an antenna supporting multiple frequency bands may be used. In some embodiments, a multi-antenna setup's antennas may be isolated from each other.

[0157] In some embodiments, a multi-antenna setup may improve the localization performance of a localization unit or of a position calibration unit. In some embodiments, this may be achieved by improving reception (e.g., signal to noise, etc.). In some embodiments, the antenna and the reception electronics are configured to detect a signal strength. In some embodiments, signal strength is used to provide a relative indication of the distance to the transmitter.

[0158] In some embodiments, a directional antenna is used. In some embodiments, the antenna is configured to detect a signal bearing that may indicate the direction of source of the signal. In some embodiments, the antenna and the reception electronics are configured to allow detection of a signal's amplitude or phase. In some embodiments, knowledge of an emitted signal's amplitude or phase and a signal's detected amplitude or phase are used to provide a relative indication of the orientation or distance to the transmitter.

[0159] In some embodiments, a multi-antenna setup may allow a self-localizing apparatus' attitude to be determined. For example, in some embodiments a multi-antenna setup may be used to detect the direction of polarization of a signal. Knowledge of a signal's emitted polarization and a signal's detected polarization may provide a relative indication of the orientation of emitter (e.g., a transceiver) and receiver (e.g., another transceiver or a self-localizing apparatus).

[0160] In some embodiments, a multi-antenna setup's antennas may operate on different frequencies. For example, a multi-antenna setup may be used in a redundant transceiver network that is operating on two separate frequencies. As a further example, a multi-antenna setup may be used on a self-localizing apparatus used in a redundant transceiver network that is operating on two separate frequencies.

[0161] In some embodiments, the antenna, analog reception electronics, and digital reception electronics are configured to measure a Doppler shift of the signal. This may, for example, allow a localization unit to improve its localization estimate by providing data related to a self-localizing apparatus' movement relative to the known location of a transceiver.

[0162] In some embodiments, the advantages of a transceiver's multi-antenna setup and a self-localizing apparatus' multi-antenna setup may be combined. This may, for example, be achieved by combining knowledge of a transceiver's multi-antenna setup's properties (e.g., the transceiver's position), knowledge of the emitted signal's properties (e.g., the signal strength, the signal polarization), and knowledge of the self-localizing apparatus' multi-antenna setups' properties (e.g.,

its antenna array's resonant element's relative alignment and its reception characteristics) in a localization unit.

[0163] In some embodiments, a localization unit is used to fuse data from one or more of the following: a multi-antenna setup; a sensor; a global property sensor; a first and a second global property sensor; and a known location.

[0164] Multi-antenna setups may have technical advantages. In some embodiments, a multi-antenna setup may allow reception to be optimized, a signal-to-noise ratio to be improved, or a data rate to be increased. This may, for example, be achieved by allowing better reception over a range of receiver positions or orientations. As another example, a multi-antenna setup may be used to implement spatial multiplexing in a MIMO system to increasing data rate.

[0165] In some embodiments, the system components' influence on localization signals is known. For example, the transceiver's RF components may have well known transmission properties. As a further example, the self-localizing apparatus' electronics and structural components have a well-known RF response. In some embodiments, known RF effects are compensated for by a compensation unit. In some embodiments, antennas may use shielding.

[0166] It will be understood that while transceivers **130** of FIGS. **2-4** have been described in different embodiments as having wireless transmission and wireless reception capabilities, the wireless reception capability is optional. For example, in some embodiments, transceivers **130** do not include the wireless reception components. In some embodiments, transceivers **130** are configured to exchange synchronization information and other information with other transceivers **130**, scheduling unit controller **120**, or scheduler **110** using wired connections. As mentioned above, the transceivers are also referred to as anchors. Accordingly, it will also be understood that anchors as used herein can include both wireless transmission components and wireless reception components or only wireless transmission components.

[0167] FIG. **5** is a block diagram of an illustrative self-localizing apparatus **140** in accordance with some embodiments of the present disclosure. Self-localizing apparatus **140** comprises an antenna **502** for receiving localization signals **202**. Antenna **502** is operationally coupled to analog reception electronics **504**, which may amplify the signal. Digital reception electronics **506** may then be used to timestamp the signal in reference to clock **508**. A synchronization unit **510** may compare an input from clock **508** to inputs from other clocks (e.g., received as part of a synchronization signal or message from another part of the localization system and received by the digital reception electronics **506**). Synchronization unit **510** may use this information to compute a clock correction for a clock rate or a clock offset, which it may communicate to localization unit **512** or compensation unit **516**, or store in a memory **518**. Additionally, information from compensation unit **516** may be used.

[0168] Self-localizing apparatus **140** of FIG. **5** may be used, for example, with localization system **100** of FIG. **2**. In this embodiment, self-localizing apparatus **140** of FIG. **5** receives timestampable localization signals **202** transmitted by transceivers **130** of FIG. **2** through its antenna **502**, analog reception electronics **504**, and digital reception electronics **506**. Self-localizing apparatus **140** may use signals **202** to compute its location relative to transceivers **130**. In some embodiments, this is achieved by timestamping signals **202**, converting the timestamps to distances, and using these distances to compute the relative location. This conversion can use an estimation of the speed of the signals **202** in the transmission medium (e.g., the speed of light in air). This conversion may be accomplished using localization unit **512**. Localization unit **512** may compute the self-localizing apparatus' location relative to the known locations of transceivers **130** by trilateration or multilateration. Sufficiently accurate timestamping may be provided by digital reception electronics **506** and clock **508**.

[0169] Reception electronics **504**, **506** may accurately determine the reception times at which the transmitted signals reach antenna **502**. Determining a signal's reception time ("timestamping") may be carried out by determining the time at which a symbol is detected. For transmissions that follow

the IEEE 802.15.4 standard, a common choice for the symbol to be timestamped is the beginning of the start-of-frame delimiter (i.e., the point at which the transmitted signal changes from the repeated transmission of a preamble code to the transmission of the start-of-frame delimiter). Digital reception electronics **506** uses a signal provided by the apparatus' clock **508** as a reference in this timestamping process. The timestamp may be therefore expressed relative to this clock. In some embodiments, clock **508** comprises an onboard clock. Reception electronics **504**, **506** may also provide additional metrics related to received signals **202**.

[0170] Quality metrics may, for example, include signal strength, reception time standard deviation, or noise properties of the signal. Quality metrics may be computed based on absolute values (e.g., an absolute signal strength) or based on relative values (e.g., a difference of signal strengths). Quality metrics may also be computed by comparing signals. For example, quality metrics may be computed based on comparisons of a signal over time, on comparisons between signals from different transceivers, on comparisons of signals received from different directions, on comparisons of signals with thresholds, on comparisons of signals with their expected property, and others. Comparisons may use individual signal properties (e.g., the peak power) or entire signals (e.g., the signal's spectral shapes). Quality metrics may, for example, be used to determine whether a signal **202** travelled in line of sight, or what material it may have traversed, or how it may have been reflected.

[0171] Self-localizing apparatus **140** of FIG. **5** (and FIG. **2**) may further comprise a global property sensor **520**. Global properties may allow a more accurate computation of the relative location of a self-localizing apparatus **140** by providing additional reference data with respect to a reference point (e.g., a transceiver or a coordinate system). This can be achieved by equipping at least one transceiver **130** and a self-localizing apparatus **140** to detect the global property. The localization system's accuracy may be improved by a method comprising the steps of: (i) transmitting a transceiver's global property reading to an apparatus, by (ii) comparing the transceiver's reading of the global property at its location and the apparatus' reading of the global property at its location, by (iii) using a model of the global property ("global property model") to translate the comparison into data related to an orientation, position, or movement, and (iv) appropriately fusing that data with other sensor data by using an estimator. Steps (ii) and (iii) may be accomplished using a localization unit **512**, such as the one shown as part of self-localizing apparatus **140** of FIG. **5**. Global property models allow conversion of one or more readings of the global property into data that can be processed by the localization system (e.g., the equation describing atmospheric pressure as a function of altitude/height). Models can take various forms, such as functions or look-up tables.

[0172] The use of data from one or more global property sensors (e.g., global property sensor **228** of FIG. **3**) in addition to other data provided by the localization system such as data from a local, onboard sensor (e.g., onboard sensor **514** of FIG. **5**), may be particularly useful in the presence of systematic sensor errors or sensors with a high noise rate. For example, in an exemplary embodiment for an outdoor installation, an apparatus and multiple transceivers may be equipped to receive GPS signals in addition to localization signals **202**. This may allow self-localizing apparatus **140** to not only determine its position relative to transceivers **130**, but also relative to a global reference frame using localization unit **512**. Additionally, this combination of localization modalities may allow detection of erroneous data by comparing readings from two independent measurement systems. The localization system may be further improved by equipping the transceivers and the apparatus with additional sensors to detect global properties, such as barometers. This may be particularly useful to allow localization unit **512** to achieve more accurate, more reliable, or faster localization in the vertical direction, for which both GPS and local localization systems may provide poorer information because of unfavorable positioning of transceivers (often all on the ground plane, below apparatuses) and GPS satellites (high in the sky, typically high above apparatuses).

[0173] Global signals may also be used to determine the relative orientation of a communicating transceiver's antenna **212** and a self-localizing apparatus' antenna **502**, which can have an important influence on signal quality or group delay and hence on their computed relative location. Determining orientation can, for example, be achieved by detecting the gravity vector of the transceiver (e.g., using an accelerometer), communicating this information to the apparatus (e.g., as part of the payload of the localization signal), and comparing it with the gravity vector detected by the apparatus (possibly corrected for the influence of apparatus' motion) using a model for each of the transceiver's and apparatus' antenna orientation relative to their accelerometer. This comparison can be performed by a compensation unit (e.g., compensation unit **516** of FIG. **5**).

[0174] As mentioned above localization unit **512** uses data to compute a location estimate. The data may include received signals **202**, data from one or more onboard sensors **514**, data from one or more offboard sensors (e.g., global property sensor **228** of a transceiver), or other data. Data related to received signals **202** may include payload, timestamps, signal characteristics (e.g., signal strength, peak shape, etc.), or others. This may be achieved by computing an estimate of the position (and, possibly, orientation or motion) of self-localizing apparatus **140** based on fusing current values of the data and other information (e.g., knowledge of input history, a dynamic model of the apparatus) using an estimator. Each individual received signal **202** may be used recursively to provide an updated (posterior) position estimate by merging it with a previous (prior) estimate. In some embodiments, (extended) Kalman Filters, complementary filters, particle filters, Luenberger observers, or any other suitable technique can be used to recursively compute an estimate. Localization unit **512** may collect several localization signal receptions (e.g., 3, 4, 5, 6, 7, 8, 9, 10, etc.) by storing them in memory (e.g., memory **518**) and batch-processing them (either after receiving a predefined number of signals, or at fixed intervals). Batch-processing methods may be based on multilateration techniques by solving the time difference of arrival (TDOA) measures for the position of the apparatus **140**. In some embodiments, a combination of recursive and batch processing may be used.

[0175] Memory **518** may be used to store information, such as data from received signals **202**, for batch processing the current location estimate or parameters for the recursive computation and sensor fusion. Localization unit **512** may also use data (e.g., compensation values) from a compensation unit or information about received signals **202** generated by the digital reception electronics **506** (e.g., quality metrics).

[0176] A reason for variation in signal quality or group delay may be that transceivers and self-localizing apparatuses are small and may operate in relative proximity to each other. This may result in a large variety of relative orientations, relative distances, and relative directions of transmitter antenna **212** to receiver antenna **502** used in a typical application and encountered during typical use, such as multiple transceivers situated on a plane with apparatuses operating above or below the plane, or multiple transceivers situated around a volume with apparatuses operating inside the convex hull of the volume.

[0177] Unlike in other localization systems, here signals **202** arriving at the self-localizing apparatus can be of varying quality or can have different group delay. In some embodiments, localization unit **512** may be used to improve the location estimate over prior localization systems by using specifics of localization signals as well as quality metrics related to the received localization signal, such as those provided by reception components (e.g., UWB peak signal strength, UWB peak shape). This may, for example, be achieved by relating the measurement variance to a signal metric such that measurements with higher variance have a lower impact on the localization unit's state estimate. As another example, the localization unit may put more emphasis on data that is independent of the localization signal (e.g., inertial sensors, global properties). As another example, the localization unit may entirely discard measurements from certain transceivers that do not meet a quality metric such as a minimum signal quality or group delay.

[0178] Unlike prior systems, localization unit **512** may here be situated on self-localizing apparatus

140 because the timestampable localization signals travelling from the transceivers to the self-localizing apparatus can contain enough information to allow the apparatus to self-localize. For example, transceivers may be synchronized and their locations may be known to the apparatus.

[0179] FIG. **6** is an illustrative timing diagram, which depicts the propagation of a received localization signal (e.g., a UWB signal) through a self-localizing apparatus' antenna **502**, analog reception electronics **504**, and digital reception electronics **506** in accordance with some embodiments of the present disclosure. The interconnection of these components will be referred to as the reception pipeline. Each of these components introduces a delay to the propagation of the received signal. Time is shown on the vertical axis, where the notation .sub.At is used to indicate that time t is measured with reference to the clock of self-localizing apparatus A.

[0180] Considering a signal that arrives at time .sub.At.sub.0.sup.Rx **602** at antenna **502** of a self-localizing apparatus, the signal propagates through the reception pipeline, before its arrival is timestamped at time .sub.At.sub.0 **606** by digital reception electronics **506**. The delay introduced by the pipeline (given by the difference between .sub.At.sub.0 **606** and .sub.At.sub.0.sup.Rx **602**) is denoted .sub.Aδ.sub.0 **604** and is referred to as pipeline delay. Consider now a second signal that arrives at time .sub.At.sub.1.sup.Rx **612** at antenna **502** of the self-localizing apparatus and, after a pipeline delay of .sub.Aδ.sub.1 **614** through the reception pipeline, is timestamped at time .sub.At.sub.1 **616**. The variation in pipeline delay between the two signals is given as |.sub.Aδ.sub.1−.sub.Aδ.sub.0|. Note that this measurement is with respect to the clock of the self-localizing apparatus **140**, and is thus independent of clock-rate offsets. In some embodiments, the difference between pipeline delays **604** and **614** is less than 0.01, 0.6, 3, or 15 nanoseconds, which allows more accurate localization to be achieved.

[0181] Variation in pipeline delay is influenced by physical, measurable factors including the frequency response of the self-localizing apparatus' antenna **502**, internal amplification and the accuracy and variation in the generation of timestamps by digital reception electronics **506**. Since antennas are non-ideal electromagnetic devices, their frequency response is described by a reception-angle-dependent magnitude response corresponding to how much a radio signal is amplified or attenuated by the antenna, as well as a reception-angle-dependent phase response corresponding to how much a radio signal is delayed by the antenna. These responses are deterministic functions of the angle at which a signal is received and result in an electrical delay of the signal as it passes through antenna **502**. In some embodiments, the signal's propagation through the analog reception electronics **504** and digital reception electronics **506** may be further delayed by internal amplification of the signal to achieve a consistent signal level, irrespective of received signal strength. Furthermore, the ability of digital reception electronics **506** to consistently and accurately timestamp the arrival of an UWB signal requires it to consistently and accurately identify the signal's "first-path". Errors in this identification, which are discussed below, result in a non-constant error in the timestamping process and thus a perceived delay in the signal's propagation time through the reception pipeline. In addition to systematic pipeline delays, in some embodiments random, external or unmodelled processes may also affect the pipeline delay, introducing non-systematic delays in the reception pipeline. In some embodiments, temperature is an example of such a process, whereby changes in temperature may influence the processing time required by digital reception electronics **506**.

[0182] The effect of a non-constant pipeline delay is the introduction of non-constant error in the reception time of any signal **202**. It will therefore be apparent to one skilled in the art that a non-constant pipeline delay, as illustrated in FIG. **6**, may correspond to a non-constant error in any time-of-arrival or time-distance-of-arrival measurement derived from the reception times of any signals **202**. A compensation unit (e.g., compensation unit **516** of FIG. **5**) may, in some embodiments, compensate for this systematic, yet non-constant error.

[0183] FIG. **7** is a block diagram of an illustrative self-localizing apparatus comprising a pair of first and second self-localizing apparatuses **140***a*, **140***b* in accordance with some embodiments of

the present disclosure. Self-localizing apparatuses **140***a*, **140***b* are physically coupled together using a structural element **700**. Each self-localizing apparatus **140***a*, **140***b* comprises an antenna **502***a*, **502***b*, analog reception electronics **504***a*, **504***b*, digital reception electronics **506***a*, **506***b*, and a localization unit **512***a*, **512***b*. As illustrated, the pair of localization units **512***a*, **512***b* are operationally coupled using communication path **702**. Communication path **702** allows localization units **512***a*, **512***b* to exchange data related to their location (e.g., their current location estimate).

[0184] Structural element **700** provides a rigid or semi-rigid attachment between self-localizing apparatuses **140***a*, **140***b*. In some embodiments, structural element **700** may include one or more of printed circuit board (PCB) mounts, multi-purpose enclosure boxes, struts, or connecting rods, among others. Because self-localizing apparatuses **140***a*, **140***b* are physically connected, their relative location is fully or partially known. This may allow first localization unit **512***a* to improve its location estimate based on data related to the location of second localization unit **512***b* and data related to the known relative location of first and second localization units **512***a*, **512***b*.

[0185] In some embodiments, the pair of self-localizing apparatuses **140***a*, **104***b* shown in FIG. **7** may operate as redundant self-localizing apparatuses, which can provide a safeguard against failure. For example, if a component in first self-localizing apparatus **140***a* fails, a localization system may rely on second self-localizing apparatus **140***b*. Depending on the use case, redundancy can be achieved for some or all of the self-localizing apparatus's components.

[0186] As illustrated, first and second self-localizing apparatuses **130***a*, **130***b* use different antennas **502***a*, **502***b*. In some embodiments, antennas **502***a*, **502***b* may have different characteristics. For example, antennas **502***a*, **502***b* may differ in their orientation, in their antenna polarization, or in their gains, among other factors. This may result in technical advantages, including an improved signal-to-noise ratio or less variation in signal reception while the self-localizing apparatus moves.

[0187] In some embodiments, a self-localizing apparatus' antennas **502***a*, **502***b* may be used to implement a multi antenna setup. A multi-antenna setup may comprise some separate electronics **504***a*, **504***b*, **506***a*, **506***b* for an individual resonant element. For example, a multi-antenna setup may comprise separate reception electronics for an antenna.

[0188] In some embodiments, self-localizing apparatuses **140***a*, **140***b* further comprise respective sensors **514***a*, **514***b*. Each sensor **514***a*, **514***b* is operationally coupled to a respective localization unit **512***a*, **512***b*. Sensors **514***a*, **514***b* may allow the corresponding self-localizing apparatus to improve its localization. In some embodiments, first localization unit **512***a* may communicate data related to its location (e.g., its current location estimate, its sensor **514***a* readings) to second localization unit **512***b*. This may allow second localization unit **512***b* to improve its location estimate.

[0189] It will be understood that the pair of self-localizing apparatuses of FIG. **7** can be used in place of a single self-localizing apparatus depicted in FIGS. **2** and **5**.

[0190] FIG. **8** is a block diagram of an illustrative self-localizing apparatus **140** comprising multiple selectable antennas **502***a*, **502***b*, **502***c* in accordance with some embodiments of the present disclosure. Self-localizing apparatus **140** further comprises a radio frequency switch (RF switch) **800** that selects a specific one of antennas **502***a*, **502***b*, **502***c* for use. In some embodiments, RF switch **800** comprises a single-pole-double-throw (SPDT) or multiport (SPnT) switch. The parameters of RF switch **800** (e.g., frequency range, isolation, switching speed, etc.) may be optimized to fit the particular use case. As illustrative in FIG. **8**, RF switch **800** is used as a multi-antenna setup. In some embodiments, antennas **502***a*, **502***b*, **503***c* may have different characteristics. For example, antennas **502***a*, **502***b*, **503***c* may differ in one or more of the following characteristics orientation, polarization, gains, antenna type. Localization unit **512**, or other components of self-localizing apparatus **140**, may control RF switch **800** to select one of the multiple antennas based on localization information. The localization information may include, for example, one or more of the position of the self-localizing apparatus, the orientation of the self-localizing apparatus, the next localization signal to be received, a quality associated with one or

more antennas, the type of antenna, and any other localization information. It will be understood that in some embodiments, RF switch **800** and multiple selectable antennas **502***a*, **502***b*, **502***c* may be used with any other self-localizing apparatus of the present disclosure.

[0191] FIG. **9** is a block diagram of an illustrative localization unit **512**, which includes a location update process, in accordance with some embodiments of the present disclosure. The localization algorithm depicted in FIG. **9** takes the form of an extended Kalman filter (EKF). Localization unit **512** may be used with any suitable self-localizing apparatus **140** of the present disclosure. At the beginning of a cycle, localization unit **512** performs a process update step **920**, where it uses the previously estimated state of the apparatus and, if available, data from control unit **940** that is indicative of the signal sent to one or more actuators. The result of this step is a prior estimate **922** (e.g., an estimate of the current state of an apparatus **140** that does not take into account any newly taken measurements). This prior estimate is then fused with available measurements. The prior estimate, measurements, and other data used by the localization unit **512** may be temporarily stored in a memory (not shown).

[0192] A first kind of measurement is the reception of a localization signal **202**. In this case, timestamp **900** of the received signal is first processed by a clock correction **902** (using data from synchronization unit **510**) and an effect compensation **904** (using data from compensation unit **516**). The resulting corrected time of arrival **906** represents an estimate of when the localization signal reached the self-localizing apparatus antenna **212**, which may then be fused with the prior estimate in an EKF measurement update step.

[0193] As stated above, the resulting corrected time of arrival **906** represents an estimate of when a localization signal **202** reached the apparatus' antenna **212**. In some embodiments, transmission information is included in the payload of the received localization signal, which represents when the signal was transmitted and by which transceiver **130**. The transmission information, together with the corrected time of arrival, is a measure for the distance between apparatus **140** and transceiver **130**. In localization unit **512**, the corrected time of arrival and the transmission information may then be fused with the prior estimate in an EKF measurement update step **924**.

[0194] A second kind of measurement, if new data is available, is data representative of a local measurement of a global property (e.g., from global property sensor **520**). This data is then compared to data representative of remote measurement(s) (provided by digital reception electronics **506**) of that global property (e.g., from global property sensor **228**) at compare **912**, and a global property model **914** provides information on how this comparison relates to the location, orientation, or motion of a self-localizing apparatus **140**. This information may then be fused into the state estimate in an EKF measurement update step **924**. An example of a global property is the signal strength of a wireless signal. The free-space path loss of a radio frequency signal of frequency f transmitted over a distance d is:

[00001] $FSPL(dB) = 20\log10(d) + 20\log10(f) + K,$

[0195] with K being a constant that depends on the units used for d and f. Through this equation, the distance of the self-localizing apparatus to the source of the wireless signal may be related to the distance of the transceiver(s) **130** to the same source.

[0196] A third kind of measurement, if new data is available, is from a sensor such as sensor **514**. Such a measurement may also be fused into the state estimate in an EKF measurement update step **924**.

[0197] Synchronization unit's **510** estimate of the local clock behavior and compensation unit's **516** estimate of compensation values may depend on the estimated location computed by the localization unit **512**. This dependence may be resolved by first using the prior location estimate to compute clock behavior and compensation values, and by then computing a new posterior location estimate **926**. This dependency may also be resolved by estimating the clock behavior or clock correction, compensation values, and location in parallel, or iteratively by alternating between 1) the computation of new clock behavior or clock correction and compensation value computation

using the current location estimate; and 2) location estimation using the current clock and compensation values until the computed values have substantially converged.

[0198] In some embodiments, localization unit **512** and the other components depicted in FIG. **9** may be integrated with a mobile robot. In such a configuration, control unit **940** may be configured to compute actuator commands based on the location computed by localization unit **512** for controlling the mobile robot.

[0199] FIG. **10** shows an illustrative mobile robot **1000** that includes a self-localizing apparatus **140** in accordance with some embodiments of the present disclosure. Mobile robot **1000** may also include one or more sensors (e.g., MEMS sensors and sensors **514**). In some embodiments, mobile robot **1000** includes an accelerometer **1006** and a gyroscope **1008**. In some embodiments, mobile robot **1000** additionally includes one or more of magnetometers, barometers, a GPS receiver, and proprioceptive sensors (e.g., sensors to monitor battery level and motor currents). Mobile robot **1000** as illustrated also includes actuators **1004** (e.g., four motors) that are used to rotate four propellers **1010** that allow the mobile robot to stay airborne and to control its movement through the space. In some embodiment, actuators **1004** are powered by a battery. In some embodiments, transceivers or apparatuses are powered by batteries.

[0200] Self-localizing apparatus **140** of FIG. **10** may be integrated with mobile robot's **1000** electronics (e.g., central processing electronics **1002**). For example, apparatus **140** may have access to mobile robot's **1000** sensors (e.g., sensor **514**, accelerometer **1006**, and gyroscope **1008**). This may, for example, be useful or convenient to achieve a certain weight distribution on a flying robot, to allow for better antenna reception, or to co-locate related electronic components.

[0201] Depending on the application, flight electronics may be more complex than the embodiments described here and may, e.g., comprise multiple electronic processing units, multiple antennas, or multiple self-localizing apparatuses.

[0202] FIG. **11** is a block diagram of an illustrative control unit **940** that may be used, for example, with mobile robot **1000** of FIG. **10** in accordance with some embodiments of the present disclosure. Control unit **940** uses cascaded controllers (horizontal controller **1102**, vertical controller **1110**, reduced attitude controller **1120**, yaw controller **1130**, and body-rate controller **1142**, with reference signal/feedback signal flow omitted for clarity).

[0203] The control scheme depicted in control unit **940** is used to follow desired vehicle position and yaw trajectories. The onboard control comprises four separate loops: horizontal **1102** and vertical position control **1110** loops, a reduced attitude control **1120** loop and a yaw control **1130** loop. It will be understood that the reference numerals used for controllers within control unit **940** of FIG. **11** are also used to refer to control loops associated with the controllers. The output of the four control loops are the three body rate commands to the flying mobile robot **1000** shown in FIG. **10**, and the collective thrust produced by the mobile robot's four propellers **1010**.

[0204] The control strategy shown in FIG. **11** is based on a cascaded loop shaping design strategy. The controller design is therefore split into the design of several controllers of lower-order dynamic systems. The vertical control loop **1110** is shaped such that it responds to altitude errors like a second-order system with collective thrust c **1112**. Similarly, to the vertical control loop **1110**, the two horizontal control loops **1102** are shaped to behave in the manner of a second-order system. However, no control inputs are directly calculated but commanded accelerations a(x) **1104** and a(y) **1106** are given as set points to the attitude controller **1120**. The attitude controller **1120** controls the reduced attitude of the mobile robot such that commanded accelerations a(x) **1104** and a(y) **1106** are met. The commanded accelerations are then converted to commanded rotation matrix entries. Using the rotational kinematics of the mobile robot, the rate of change of the matrix entries can be used to compute the desired vehicle body rates p **1122** and q **1124**. The controllers described above fully define the translational behavior of the mobile robot. The yaw controller **1130** may then be implemented as a proportional controller from the measured yaw angle to compute the desired yaw rate r **1132** (e.g., as measured by a sensor **514** on the mobile robot **1000**). Body-rate controller **1142**

receives current body rates (measured or estimated), desired vehicle body rates p **1122**, q **1124**, and r **1132** and together with collective thrust c **1112** control unit **940** outputs actuator commands f.sub.1, f.sub.2, f.sub.3, f.sub.4 **1144** to actuators **1004** to cause movement **1146** of mobile robot **1000**.

[0205] FIG. **12** shows an illustrative transceiver network including multiple transceivers **130** in accordance with some embodiments of the present disclosure. Such a transceiver network may allow for the use of a self-localizing apparatus **140** in a wide geographic area by allowing for the simultaneous use of a large number of transceivers. As shown in FIG. **12**, in the case where transmission ranges **1400** of two transceivers overlap, the transceivers will be referred to as "interfering", because simultaneous transmission of localization signals **202** by both transceivers may result in the localization signals **202** interfering. A transmission range may, for example, be defined as the boundary of the area where the signal strength of the transmitted signal drops below the receiver sensitivity. To avoid signal interference, the signal emissions of transceivers in a particular area are typically coordinated. In some embodiments, this may be achieved by ensuring adequate separation of signals in time (e.g., through sufficient time between the emission of two signals, e.g., using a scheduling unit), in space (e.g., through sufficient geographic separation of transceivers, by regulating the transmission power), in frequency (e.g., through sufficient separation of the localization signals' transmission carrier frequencies (center frequency) or bandwidth, e.g., using a scheduling unit), or in preamble properties (e.g., preamble code, preamble modulation).

[0206] The amount of time required for sufficient signal separation in time may depend on many factors (e.g., strength of the signal, size of a signal packet, pulse/peak shape of the signal, transceiver's antenna, receiver's antenna, the geographic location of transceivers (including their geographic separation), obstacles, background noise, etc.). Ensuring time separation of signals may mean that the duration between subsequent signals from any particular transceiver increases as the number of transceivers grows. This can be particularly problematic for dynamic autonomous mobile robots, where even relatively small reductions in update rates may result in a significant degradation in localization performance. A known method of ensuring time separation is Time Division Multiple Access (TDMA). Aloha methods may also be utilized in embodiments where occasional signal interference is acceptable, and where signal timing is unimportant.

[0207] Sufficient separation in space, related to the transmission range of each transceiver, may depend on many factors (e.g., strength of the signal, frequency of the signal, bandwidth of the signal, pulse/peak shape of the signal, transceiver's antenna, receiver's antenna, the geographic location of transceivers (including their geographic separation), obstacles, background noise, etc.). In some embodiments, typical spatial separation is 1-100 meters. In some embodiments, typical spatial separation is 10-500 meters. In some embodiments, typical spatial separation is 200-2000 m. In some embodiments, typical spatial separations are on the order of kilometers. In some embodiments, two transceivers may be co-located. In some embodiments, combinations of spatial separations are used. In FIG. **12**, transmission range **1200** is graphically represented as a circle for simplicity; however, it will be apparent to one skilled in the art that transmission range **1200** may be a more complex shape. When ensuring space separation of transmissions, it may be desirable to locate transceivers **130** such that a self-localizing apparatus **140** would be capable of receiving transmissions from a predetermined number of transceivers **130** at every point within a defined geographic area. This number of transceivers **130** may depend on many factors (e.g., desired update rate, desired system robustness, time separation of the transmissions, frequency separation of the transmissions, background noise, obstacles, etc.).

[0208] Achieving sufficient separation in space may be further aided by the selection of suitable antennas. Some embodiments use directional antennas. Some embodiments use omnidirectional antennas. In some embodiments, directional antennas are used to help ensure space separation of localization signals. In some embodiments, by directing the transmissions of transceivers **130** using

directional antennas, it may be possible to more accurately control which transceivers **130** transmit to which regions of a defined space and thus more accurately control the space separation of localization signals **202**. In some embodiments, by directing the transmissions of transceivers **130** using directional antennas, it may be possible to achieve a longer transmission range in a desired direction. Other methods that may aid spatial separation include shielding, placement (e.g., away from noise sources), optimizing radiation patterns, and combinations of the above. In some embodiments, by equipping a self-localizing apparatus **140** with a directional antenna, orientation information can be estimated based on a comparison of which signals are received with the known locations of transceivers **130**.

[0209] In some embodiments, transceivers **130** are arranged such that coverage of a desired operating area is optimized with respect to some metric. In some embodiments, a transceiver's **130** operation is optimized with respect to some metric. Suitable metrics may include the number of transceivers in range, a signal strength, update rate from a specific combination of transceivers, multipath effects, or others, including combined metrics. Transceiver arrangement may comprise a transceiver's location, a transceiver's antenna orientation, a transceiver's operating frequency, a transceiver's bandwidth, or other factors. An operating area may be a geographic area, a flight volume for a flying robot **1000**, a pre-defined operating volume, or another area. Optimization may concern physical parameters (e.g., geographic placement of transceivers, antenna orientations, etc.) or operational parameters (e.g., the operation of a scheduling unit **218**). In some embodiments, optimization may be performed by a scheduler. In some embodiments, an optimization may be pre-computed. In some embodiments, a schedule is created manually. In some embodiments, a schedule is created base on an optimization. For example, in some embodiments an optimal schedule may be determined by minimizing the number of transceivers per zone or per region, with the constraint that every point within a defined area be capable of receiving from, for example, at least three transceivers. For some problems such a schedule may ensure that a self-localizing apparatus is capable of localization in three-dimensions throughout a defined area, while further minimizing the TDOA cycle time within the cell (which can be proportional to the number of transceivers within the cell). As another example, in some embodiments a schedule may be computed as the solution of an optimization problem that weighs up the cost of a self-localizing apparatus changing frequency, with the cost of an increased TDOA cycle time.

[0210] Sufficient separation in transmission frequency may depend on many factors (e.g., strength of the signal, frequency of the signal, bandwidth of the signal, pulse/peak shape of the signal, transceiver's antenna, receiver's antenna, the geographic location of transceivers (including their geographic separation), obstacles, background noise, etc.). In some embodiments, it may be implemented using a scheduling unit. In some embodiments, separation is in the range of 1-50 MHz. In some embodiments, separation is in the range of 100-500 MHZ. In some embodiments, separation is in the range of 200-1000 MHz. In some embodiments, overlapping transmission frequencies are used. When designing for frequency separation of signals, it may be important to consider that a self-localizing apparatus **140** may need to change its reception frequency to receive the frequency-separated localization signals **202**. A known method of ensuring frequency separation is Frequency Division Multiple Access (FDMA). In some embodiments, combinations of various frequency separations are used.

[0211] In some embodiments, TDMA may be employed to ensure time separation of localization signals **202**. In some embodiments, a simple approach may be employed, whereby if the transceiver network comprises N transceivers, N time slots will be allocated, one per transceiver **130**. The time of cycling through all time slots is sometimes referred to as TDMA cycle time. In a case where all transceivers in a network are interfering, this allocation of N transceivers to N time slots is optimal in that it is the shortest amount of time that allows each transceiver to transmit once per cycle. Other optimization criteria, such as positioning performance or information propagation time, may be used. However, in the embodiment as illustrated in FIG. **13**, where not all transceivers interfere,

a different optimal TDMA allocation schedule is possible, which uses fewer than N time slots and thus decreases the TDOA cycle time, and increases the average rate at which a self-localizing apparatus **140** would receive localization signals **202**.

[0212] FIG. **13** shows an illustrative simplified transceiver network in accordance with some embodiments of the present disclosure. In FIG. **13**, transceivers **130**a and **130**b do not interfere. It will be apparent to one skilled in the art that in this case, both transceivers **130**a and **130**b may utilize the same TDMA timeslot, since it is not possible for a self-localizing apparatus to simultaneously receive signals from both transceivers because of their separation in space, and thus simultaneous transmissions will not interfere. This is illustrated in FIG. **13** by transceivers **130**a and **130**b having the same shading.

[0213] In some embodiments, a scheduling unit **218** may coordinate the scheduling of TDMA timeslots. The synchronization of multiple transceivers **130** to achieve a consistent time schedule may in some embodiments be enabled by a synchronization unit **224** or may be enabled by transceivers **130** sharing a common clock **210**. In some embodiments, timeslot allocation (i.e., the schedule) may be manually determined or programmed into the transceiver's memory (e.g., memory **230**). In some embodiments, the schedule may be computed autonomously by a scheduler. In some embodiments, the schedule determined by a scheduler may be transmitted by a scheduling unit controller.

[0214] In some embodiments, the scheduler (e.g., scheduler **110**) may operate periodically or may be triggered by a transceiver **130** through transmission of an appropriate signal **302**. In some embodiments, signal **302** is transmitted in response to an event. In some embodiments, an additional TDMA timeslot is allocated for transmission of arbitrary localization signals **202** or transceiver signals **302**. In some embodiments, usage of this TDMA timeslot is coordinated by ALOHA. In some embodiments, transceivers **130** use this TDMA timeslot to alert other transceivers **130** to the occurrence of an event. In some embodiments, this timeslot is used by a scheduling unit controller to trigger switching to a new schedule.

[0215] In some embodiments, periodic or triggered reallocation allows the network to adapt the schedule such that the allocation of TDMA timeslots compensates for transceivers joining or leaving the transceiver network. The addition of a transceiver **130** to the network may, in some embodiments, be achieved by leaving one TDMA slot unallocated to allow new transceivers **130** to announce their addition to the network and trigger a redefinition of the transmission schedule (i.e., allocation of TDMA timeslots). Removal of a transceiver **130** from the network may, in some embodiments, be achieved by enabling transceivers to monitor for non-transmission of a transceiver **130** and trigger a redefinition of the transmission schedule if a transceiver **130** has not transmitted for a predetermined number of its TDMA timeslots.

[0216] In some embodiments, a TDMA time slot length less than 0.1 ms, 0.5 ms, 1 ms, 2 ms, 2.5 ms, 5 ms, 10 ms, or 50 ms is used.

[0217] In some embodiments, a transceiver **130** may include its estimated location or timing information within the payload of its localization signals **202** or transceiver signals **302**. In some embodiments, a transceiver **130** is operable to receive these transmitted signals **202**, **302**. In some embodiments, a receiving transceiver may include a synchronization unit **224** that acts to synchronize the time schedule of the receiving transceiver with the time schedule of the transmitting transceiver, based on received timing or location information.

[0218] In some embodiments, transceivers **130** may be allocated more than one TDMA timeslot in at least one schedule, allowing them to transmit more often within one TDMA cycle. In some embodiments, allocation of multiple timeslots may, for example, be decided based on the Fisher Information added by the transceiver **130**—a heuristic known to those skilled in the art, which can be calculated based on the transceiver's relative position.

[0219] In some embodiments, Frequency Division Multiple Access (FDMA) is used to mitigate transceiver interference, whereby interfering transceivers may be allocated different transmission

frequencies such that they no longer interfere. In some embodiments, interfering transceivers may be allocated different preambles or pulse repetition frequencies to achieve a similar effect.

[0220] FIG. 14 shows an illustrative transceiver network where transceivers 130 are grouped into adjacent cells 1410 in accordance with some embodiments of the present disclosure. In some embodiments, adjacent cells 1410 may employ FDMA techniques to enable transceivers 130 from different cells 1410 to operate simultaneously and without significant interference in areas 1420 in which the transmissions overlap. In some embodiments, different cells 1410 may use different transmission parameters such as different transmission center frequencies, frequency bandwidths, preambles codes, preamble modulation schemes, or pulse repetition frequencies for the transmission of localization signals 202 such that the different cells 1410 can operate simultaneously and without significant interference. This may enable a self-localizing apparatus 140 to receive localization signals 202 anywhere in the network, even when moving through more than one cell during reception. Within each cell, TDMA may be used to coordinate the transmissions of individual transceivers 130.

[0221] FIG. 15 shows a mobile robot 1000 operating within an area 1420 serviced by multiple transceiver cells 1410 of differing frequency in accordance with some embodiments of the present disclosure. Mobile robot 1000 comprises two self-localizing apparatuses 140, which are physically coupled to mobile robot 1000. Because mobile robot 1000 is operating in an area serviced by multiple transceiver cells 1410, multiple localization signals 202 of differing frequencies may be present in area 1420 simultaneously. In some embodiments, this means that the two self-localizing apparatuses 140 coupled to mobile robot 1000, when considered together, receive localization signals 202 at a higher rate than it would if all transceivers 130 were to transmit on the same frequency and use TDMA to coordinate their transmissions. In some embodiments, by using two self-localizing apparatuses 140, this may allow one or more localization units to update a location estimate at a higher rate. In some embodiments, a communication path (e.g., communication path 702) between two self-localizing apparatuses 140 may allow a localization unit to compute the orientation as well as the location of the body (e.g., mobile robot 1000 in FIG. 15) to which the two self-localizing apparatuses are attached. In some embodiments, having multiple self-localizing apparatuses 140 may allow one or more localization units to compute location more accurately.

[0222] As explained above, a scheduler such as scheduler 110 of FIG. 1 may use one or more input parameters to determine a schedule for transmitting localization signals by anchors of a localization network. In some embodiments, the inputs to scheduler 110 include the position of the anchors and user requirements such as desired positioning performance. FIG. 16 shows illustrative input parameter maps 1610 and 1620 that can be used for determining a schedule in accordance with some embodiments of the present disclosure.

[0223] Input parameter map 1610 illustrates two input parameters. The first input parameter is the position of anchors 130. As illustrated, the localization network comprises six anchors 130. The positions of anchors 130 may be identified automatically in a calibration step, or may be determined by a user when the system is installed (e.g., from a performed survey or from available drawings to which the mounting positions can be referred). The second input parameter is the desired positioning performance of the localization network. Input parameter map 1610 illustrates contour lines of the desired positioning performance. As illustrated, the desired positioning performance is reflected using a scale from 1, which reflects high performance (e.g., performance is crucially important), to 0, which reflects low performance (e.g., where no localization performance is needed). Intermediate values between 1 and 0 signify that some localization performance is required, but a varying degree of degradation is acceptable. In some embodiments, the contour lines of input parameter map 1610 reflect discrete desired performance levels. For example, the desired positioning performance may be 0 below contour line 0, 0.5 between contour lines 0 and 0.5, 0.8 between contour lines 0.5 and 0.8, 1 above contour line 1. In some embodiments, the contour lines reflect continuous values between 0 and 1. Input parameter map

1620 is similar to input parameter map **1610**, but uses a binary map to reflect desired positioning performance. The binary positioning performance includes two regions-one region where localization is required (1) and another region where no localization is required (0).

[0224] In some embodiments, the desired positioning performance in maps **1610** and **1620** are determined by a user directly (e.g., according to a building plan from which regions of interest have been extracted) or it could be automatically generated (e.g., from known motion patterns of autonomous machines). It will be understood that maps **1610** and **1620** are merely illustrative and that the position of anchors **130** and the desired positioning performance may be inputted to a scheduler in any suitable form. For example, the positions of anchors **130** may be inputted using the coordinates of anchors **130** in a coordinate system. As another example, the desired positioning performance may be inputted using a function that defines the position performance. As another example, the desired positioning performance may be inputted using an array of values that define the positioning performance within a coordinate system. As another example, the desired positioning performance may be inputted using the shape or location of contour lines.

[0225] In some embodiments, input parameter maps are static maps that are generated upon initialization of a localization system and are not changed until a subsequent initialization or calibration of a localization system. In some embodiments, input parameter maps change over time and therefore can be dynamic. FIG. **17** shows an illustrative dynamic positioning performance map **1710** used for determining a schedule in accordance with some embodiments of the present disclosure. Map **1710** comprises a plurality of different frames that show how localization coverage requirements change over time. The shaded portion of each frame indicates the region where localization coverage is needed. The unshaded portion of each frame indicates regions where localization coverage is not needed. As illustrated, positioning performance map **1710** is a binary map. The consecutive frames of map **1710** show snapshots of a binary performance map that is parametrized in time. Such a map could be stored as a dense series of snapshots, as a sparse series of snapshots (using interpolation techniques between the snapshots), using parametric models (e.g., using periodic functions), using any other suitable, or using any other suitable technique. It will be understood that the binary nature of positioning performance map **1710** this is merely illustrative and that map **1710** may also be implemented using continuous values or using multiple discrete performance levels.

[0226] FIG. **18** shows an illustrative example of how a schedule can be adjusted in accordance with some embodiments of the present disclosure. In some embodiments, the schedule can be adjusted in real-time based on localization requirements. As shown in the top left portion of panel **1810**, location map **1820**a shows the location of three mobile robots **1000** within a coordinate system. Each of mobile robots **1000** may include one or more self-localization apparatuses **140** and be configured to transmit its location back to the localization network. For example, mobile robots **1000** may be configured to wireless transmit (e.g., via antenna **502** of a self-localizing apparatus **140**) their locations back to one or more anchors of the localization network. Mobile robots **1000** may also transmit additional information to the localization network such as their current velocities or planned motions. From this information, coverage requirement map **1830**a can be extracted. In some embodiments, a scheduler such as scheduler **110** may receive the information from mobile robots **1000** and generate coverage requirement map **1830**a. In some embodiments, coverage requirement map **1830**a can be generated by requiring coverage for a fixed radius surrounding the current position of each mobile robot **1000** and also for a fixed radius around the planned motion paths of the mobile robots.

[0227] Coverage requirement map **1830**a can be used by the scheduler to compute an appropriate schedule **1840**a for the given requirements. Depending on the trade-off between positioning performance and computational complexity, the scheduler may select the most appropriate among a series of pre-computed and stored schedules, or it may compute a new, optimized, schedule based on requirement map **1830**a. Information regarding schedule **1840**a may be transmitted to one or

more control units of the localization network for controlling the transmission of localization signals from the anchors of the network.

[0228] In some embodiments, the scheduler transmits information about the schedule **1840***a* to a scheduling unit controller, which in turn transmits a signal to the anchors which then causes the anchors to transmit according to the schedule. When schedule **1840***a* is pre-computed schedule, the scheduling unit controller may only send a signal indicative of which schedule to use (e.g., "use schedule nr. 3"). When schedule **1840***a* is a newly computed schedule, the scheduling unit controller may transmit the new schedule to the anchors and then signal the change of schedule once the anchors have received it.

[0229] The process described may be repeated at a later time to adjust the schedule in real-time. As shown in the bottom portion of panel **1810**, the locations of mobile robots **1000** have changed in location map **1820***b*. The new locations depicted in location map **1820***b* may be used to generate a new coverage requirement map **1830***b*, which in turn can be used to determine schedule **1840***b*. Schedule **1840***b* can then be used to control the transmission of localization signals from the anchors of the network as described above.

[0230] FIG. **19** shows another illustrative example of how a schedule can be adjusted in accordance with some embodiments of the present disclosure. In this example, a group of mobile robots **1000** is moving in a relatively large space according to a predefined set of trajectories and a set of anchors is distributed among the entire space. Location maps **1910***a*, **1910***b*, **1910***c*, and **1910***d* show the locations of the mobile robots **1000** as they move along the predefined set of trajectories. Specifically, the group starts in the lower-right quadrant and then moves counter-clockwise through the four quadrants. To improve the positioning performance of the localization network, one may want to use only a subset of the anchors that are in close proximity to the group of mobile robots **1000** and configure the other anchors to not transmit. In location map **1810***a*, because mobile robots **1000** are located in the bottom right quadrant, it may be desirable to not use anchors in the top-left quadrant. For example, these anchors may be too far away from mobile robots **1000** for their signals to be successfully received. It may also be desirable to have mobile robots **1000** receive localization signals at a relatively high rate and not using anchors that are far away may increase the rate at which localization signals could otherwise be received by mobile robots **1000**.

[0231] Accordingly, in some embodiments, the schedule may be adjusted so that only anchors located within region A are used to transmit localization signals. In other embodiments, the schedule may be adjusted so that a subset of anchors is used to only provide localization capability in region A. As shown in FIG. **19**, as the location of the group of mobile robots **1000** changes over time, region A follows them through the four quadrants. As a result of these schedule changes, the area where the mobile robots can localize themselves (region A) moves over time. The adjustment to the schedule can be achieved in several ways. In one case, the transmission schedule could be changed periodically based on the position of the group of mobile robots **1000**. This could be done in an open loop fashion, assuming that a centralized unit knows the target position of the mobile robots, or in a closed loop fashion based on position information provided by the mobile robots. Thus, different schedules can be used over time. In another potentially more sophisticated example, the adjustments can be accomplished using a single long schedule that is synchronized with the movement of the mobile robots (e.g., the schedule can be started when the mobile robots start moving or a certain amount of seconds before) and has a duration which is at least as long as the duration of the mobile robot trajectories.

[0232] While FIG. **19** shows adjusting a schedule based on the location of one group of mobile robots, a schedule can also be adjusted based on two or more groups of mobile robots. FIG. **20** shows an illustrative example of how a schedule can be adjusted for two groups of mobile robots in accordance with some embodiments of the present disclosure. In this case, the mobile robots are organized in two different groups which move according to different sets of trajectories.

[0233] This presents a technical problem of how to configure the schedule to accommodate and

optimize the transmission of localization signals. In some embodiments, it may be convenient to organize the anchors of the localization network in two clusters and define the schedule in such a way that the mobile robots of the first and second groups can localize and receive data from the anchors (e.g., commands) independently. This can be achieved, for example, by using two different carrier frequencies for the two clusters or by setting the transmission power in such a way that the transmission of the anchors allocated to the first group of mobile robots does not interfere with the transmission of the anchors dedicated to the second group of mobile vehicles.

[0234] As shown in location map **2010***a*, a first group of mobile robots starts from the top of the space, within cluster A, while a second group starts from the bottom, within cluster B. The schedule may cause a first group of anchors, cluster A, to cover the area occupied by the first group of mobile robots and a second group of anchors, cluster B, to cover the area occupied by the second group of mobile robots.

[0235] As part of the target trajectories, the mobile robots of the first group converge toward the center of the top part of the space while the mobile robots of the second group split and move to the sides of the bottom part. This is illustrated in location map **2010***b*. These movements, for example, do not require an update of the transmission schedule.

[0236] Next, the target trajectories may cause the mobile robots of the first group to move toward the bottom part, while the mobile robots of the second group move toward the upper part. This is illustrated in location map **2010***c*. To perform these maneuvers, the transmission schedule is updated to change the set of anchors that belong to cluster A and the set of anchors that belong to cluster B. This creates a central aisle for the mobile robots of the first group and two lateral corridors for the mobile robots of the second group. It is noted that in some cases the region of space covered by cluster B could overlap with the region of space covered by cluster A.

[0237] Finally, the target trajectories may cause the mobile robots of the first group to spread out within the bottom part of the space and the mobile robots of the second group to spread out within the upper part. This is illustrated in location map **2010***d*. This is achieved once again by reallocating the anchors among the two clusters.

[0238] The concept presented with this use case is that clusters can move together with the groups of mobile robots to provide the desired positioning performance in the region of space occupied by the respective groups of mobile robots.

[0239] It will be understood that while FIGS. **18-20** were described in the context of being used for localization of a mobile robot **1000**, FIGS. **18-20** can be used with any other suitable objects such as vehicles, people, or any other objects that comprises a self-localizing apparatus for receiving localization signals. In some embodiments, FIGS. **18-20** can be used with any of the embodiments of transceivers **130** and self-localizing apparatus **140** described herein.

[0240] FIG. **21** is a diagram of an illustrative structure of a localization signal **202** in accordance with some embodiments of the present disclosure. In some embodiments, the structure of localization signal **202** is similar to that defined in IEEE standard 802.15.4. The same standard describes other aspects of localization systems, such as the signal transmission process. The transmission of a localization signal **202** begins at time t.sub.start **2122** with the transmission of a preamble sequence **2110**. This sequence is typically predefined and known to both the transmitter (e.g., a transceiver **130**) and receiver (e.g., a self-localizing apparatus **140**) of localization signal **202**. In some embodiments, a preamble sequence **2110** may be stored in memory. In some embodiments, a preamble sequence **2110** may be configurable during system operation. In some embodiments, a preamble sequence **2110** may be encoded by the interconnection of digital or analog electronic components.

[0241] In some embodiments, preamble **2110** defines a sequence in which radio pulses (e.g., UWB radio pulses) are transmitted on a specific transmission channel and with a specific rate. This rate may sometimes be referred to as the pulse repetition frequency. The pulse repetition frequency is typically known to both the transmitter and receiver of a localization signal **202**. In some

embodiments, the pulse repetition frequency may be stored in memory. In some embodiments, the pulse repetition frequency may be configurable during system operation. In some embodiments, the pulse repetition frequency may be encoded by the interconnection of digital or analog components.

[0242] A receiver is typically capable of receiving a localization signal (e.g., an UWB signal) if it is configured to operate on the transmission center frequency, with the same transmission frequency bandwidth, with the same preamble code, and the same preamble modulation scheme (e.g., frequency shift or phase shift). In some embodiments, this may be achieved through appropriate configuration of the receiver's analog reception electronics (e.g., analog reception electronics **504**) or digital reception electronics (e.g., digital reception electronics **506**) or of the transmitter's analog transmission electronics (e.g., transmitter's analog transmission electronics **214**) or digital transmission electronics (e.g., digital transmission electronics **216**). In some embodiments, appropriate selection of channel or preamble **2110** or pulse repetition frequency may enable receivers to receive UWB signals from a specific subset of transmitters. In some embodiments, appropriate selection of channel or preamble **2110** or pulse repetition frequency may enable transmitters to transmit UWB signals to a specific subset of receivers. In some embodiments, appropriate selection of channel or preamble **2110** or pulse repetition frequency may allow multiple localization signals to be transmitted simultaneously, with reduced interference or with no interference.

[0243] After transmission of the preamble **2110**, the transmitter transmits a start frame delimiter **2112**, to indicate the beginning of the signal's data portion. After transmission of the start frame delimiter **2112**, the transmitter transmits a physical-layer header (PHR) **2114**, containing information pertaining to the encoding of the signal's payload **2116** (e.g., data rate). After transmission of physical header **2114**, the signal's payload **2116** is transmitted. In some embodiments, the payload is empty. In some embodiments, the payload contains information from a global property sensor **228**. In some embodiments, the payload **2116** contains information to facilitate synchronization by a synchronization unit (e.g., a synchronization unit **510**). In some embodiments, payload **2116** contains information to enable the scheduling of future transmissions by a scheduling unit (e.g., scheduling unit **218**). In some embodiments, payload **2116** contains information to enable the self-localizing apparatus to receive future transmissions (e.g., announcements of future signal transmissions that may include the transmission time, the transmission channel, the transmission preamble code, or the transmission pulse repetition frequency). In some embodiments, payload **2116** contains information pertaining to prior transmitted or received signals (e.g., signals **202** or **302**). In some embodiments, payload **2116** contains other information. In some embodiments, payload **2116** may contain multiple pieces of information. In some embodiments, payload **2116** contains error-checking information that may be used to evaluate the integrity of the received payload **2116**. Transmission of signal ends at time tend **2124** after transmission of the payload **2116**.

[0244] Through the detection and reception of a localization signal's preamble **2110**, a receiver is able to detect the transmission of a start frame delimiter (SFD) **2112**. In some embodiments, the time at which the start frame delimiter **2112** is detected is time stamped by the receiver's digital reception electronics (e.g., digital reception electronics **506**). After detection of the start frame delimiter **2112**, the receiver is able to detect the physical header **2114**. Information encoded in physical header **2114** may be used by the receiver to decode information encoded in the signal's payload **2116**.

[0245] In some embodiments, payload **2116** may be checked for errors. In some embodiments, payload **2116** may be used within other units of the receiver. In some embodiments, payload **2116** may be used to calculate a time difference. In some embodiments, payload **2116** may be used to calculate a distance. In some embodiments, payload **2116** may be compared with a measurement from the receiver's global property sensor (e.g., global property sensor **520**). In some embodiments, the payload may be stored in a memory (e.g., memory **230**, **516**).

[0246] As will be apparent to one skilled in the art, while the present embodiments disclose a specific signal's structure similar to that defined in IEEE standard 802.15.4, many other signal structures are equally valid and may be used with the present disclosure.

[0247] FIG. **22** shows an illustrative transmission schedule **2200** that may be used to achieve a higher localization update in accordance with some embodiments of the present disclosure. Transmission schedule **2200** may be used, for example, where it is not crucial for a self-localizing apparatus to receive every transmitted data payload. Transmission schedule **2200** is depicted in the form of a plot with time on the x-axis and transceiver number on the y-axis. As illustrated, transmission schedule **2200** is determined such that transceiver 1 begins the transmission of the preamble of localization signal **2202**a at time t0. The transmission duration of signal **2202**a from transceiver 1 is T, and thus the transmission will be completed at t2=t0+T. The preamble and SFD of signal **2202**a are transmitted during a first duration T′. Therefore, a self-localizing apparatus is capable of timestamping the reception time of signal at time t1=t0+T′.

[0248] At time t3, the transmission of localization signal **2202**b from transceiver 2 is scheduled. In a conventional schedule, one would choose t3>t2, such that a self-localizing apparatus is capable of completely receiving the signal from transceiver 1 before a second localization signal is transmitted. However, in this example, t3 is purposely chosen such that to <t3<t2 (i.e., the transmission of signal **2202**b from transceiver 2 begins after transceiver 1 starts its transmission, but before it completes it). In some embodiments, the transmission will be scheduled such that t1<t3<t2.

[0249] Schedule **2200** allows a self-localizing apparatus receiving the signals of the localization system to select, around time t1 or a priori, whether it is more beneficial for its performance to (1) receive signal **2202**a from transceiver 1 in full by keeping its reception electronics tuned into signal **2202**a for the entire duration T or (2) only timestamp the signal from receiver 1 but ignore its payload, and instead also timestamp signal **2202**b from receiver 2 by tuning into the signal from transceiver 1 for a duration of T′, and then aborting the reception and tuning into signal **2202**b from transceiver 2.

[0250] Schedule **2200** shows two additional signal transmissions **2202**c, **2202**d from respective transceivers **3**, **4**, where a receiving self-localizing apparatus can make a similar choice for reception.

[0251] To enable the self-localizing apparatus to selectively timestamp signals without receiving the signals in their entireties, the analog reception electronics or the digital reception electronics in the self-localizing apparatus must be operable to receive a signal through which the reception of a signal from the antenna can be limited to the timestamping of the preamble and SFD portion. In some embodiments, the digital reception electronics provide a signal when the timestamping has been completed to an interface to stop an ongoing signal reception; the signal and the interface can then be used in conjunction to stop the reception of a signal after the timestamping has been completed. In some embodiments, the digital reception electronics provide an interface where they can be configured to automatically stop a reception once the timestamping has been completed.

[0252] FIG. **23** shows a portion of the illustrative transmission schedule of FIG. **22** and corresponding receiver activity **2310** in accordance with some embodiments of the present disclosure. FIG. **23** illustrates further details of the operation of a receiver of a self-localizing apparatus when localization signals are scheduled to partially overlap. Specially, FIG. **23** shows the two partially overlapping localization signals **2202**a, **2202**b of FIG. **22**. Corresponding illustrative receiver activity **2310** is shown beneath localization signals **2202**a, **2202**b.

[0253] Before time t0, the receiver is scanning for a preamble. Shortly after the start of the preamble transmission from the first transceiver at time t0, the receiver begins to lock into the preamble sequence of localization signal **2202**a. After the transmission of the preamble and the SFD has been completed, the receiver (e.g., digital reception electronics) has timestamped the reception of the localization signal **2202**a. At this point, the receiver stops receiving the signal from

transceiver 1 and begins scanning for a new preamble. Shortly after transmitter **2** begins to transmit the preamble of localization signal **2202***b* at time t3, the receiver locks into the preamble sequence. The receiver then stays locked into localization signal **2202***b* to receive the entirety of the signal from transceiver 2, to generate a reception timestamp as well as receive the data payload of that signal.

[0254] In some embodiments, the self-localizing apparatus includes decision logic that determines whether it is more beneficial to receive a localization signal in its entirety or to only receive the portion that is required for timestamping. This decision may, for example, be based on a required minimum payload reception frequency, on a list of localization anchors from which the payload must be received (while others may only be timestamped), or logic that monitors whether sufficient information is available to interpret signals that are only timestamped (such as which anchors they are transmitted by, at what times they are transmitted, etc.).

[0255] In some embodiments, the self-localizing apparatus includes a scheduling unit that configures the receiver to receive signals in their entirety or to only timestamp them according to a schedule stored in a memory. In some embodiments, the payload of localization signals includes a schedule of future transmissions, which is used by the self-localizing apparatus to determine whether to only timestamp or to receive in their entirety future localization signals.

[0256] FIG. **24** shows an illustrative transmission schedule of localization signals **2402***a*, **2402***b*, **2402***c* comprising two payloads in accordance with some embodiments of the present disclosure. The transmission schedule of FIG. **24** is similar to FIG. **22**, but instead of there being a single payload, the payload of the localization signals is organized in two parts. The first part of the payload (payload 1) may contain information that all or most of the self-localizing apparatuses want to receive while the second part of the payload (payload 2) may contain information that is interesting for only some of the self-localizing apparatuses.

[0257] Before time t0, the receivers of self-localizing apparatuses are scanning for a preamble which is received shortly after time t0. Starting from this point the receivers can lock into signal **2402***a*, receive the SFD, and timestamp the message. Some of the receivers may decide that this information is enough and therefore stop the reception and start scanning for a new preamble. Some other receivers may be interested in receiving more information and therefore continue the reception until the first part of the payload (payload 1) is completely received. At this point, these receivers can decide whether to continue and receive the remaining part of the payload (payload 2) or interrupt the reception and start scanning for a new preamble.

[0258] The schedule shown in FIG. **24** allows self-localizing apparatuses to decide how much information is received and how frequently the desired information is received. For example, some self-localizing apparatuses may want to receive the second part of the payload every four incoming localizing signals, the first part of the payload every two incoming localizing signals, and the SFD (e.g., message timestamp) every incoming signal or whenever possible. This would allow for faster timestamping of incoming signals compared to a receiver that always receives the entire localization signal.

[0259] In some embodiments, the payload of the localization signals can be organized in three or more parts and the self-localizing apparatus can determined which parts to receive.

[0260] FIG. **25** shows an illustrative localization system **2500** and a corresponding performance map **2510** in accordance with some embodiments of the present disclosure. Localization system **2500** comprises 12 anchors labelled A to L. Performance map **2510** indicates a positioning performance of 1 for the entire localization space of localization system **2500**. Therefore, performance map **2510** indicates that the same positioning performance should be provided for the entire localization space.

[0261] Anchors A to L of localization system **2500** can be configured (e.g., using a schedule determined by a scheduler) to transmit localization signals according to any one of a number of different schedules to achieve a similar positioning performance in the localization region. In one

example, the anchors can be scheduled to transmit in alphabetical order (i.e., A-B-C-D-E-F-G-H-I-J-K-L). In another example, the anchors can be scheduled to transmit in such a way that the transmission of an anchor located on the floor is followed by a transmission of anchor located on the ceiling (e.g., A-L-C-K-D-H-E-G-F-J-B-I). This may be desirable to maximize the difference in directions that the self-localizing apparatus receives localization signals from to optimize the localization performance of the self-localizing apparatus by minimizing the dilution of precision. It is noted that both the schedules are uniform in space and in transmission rate. It is also noted that these schedules are merely illustrative and that other schedules can also be used to achieve the same positioning performance within the localization space.

[0262] FIG. **26** shows the illustrative localization system **2500** of FIG. **25** used with a different performance map **2610** in accordance with some embodiments of the present disclosure. Performance map **2610** differs from performance map **2510** of FIG. **25** in that it only requires positioning in the right part of the localization space. The left part of the localization space is not needed. For example, performance map **2610** may be used when there are no self-localizing apparatuses in the left part of the localization space.

[0263] To achieve the positioning performance required by performance map **2610**, a subset of the anchors can be configured (e.g., using a schedule determined by a scheduler) to transmit localization signals according to any one of a number of different schedules to achieve the desired positioning performance. For example, the anchors can be configured such that the anchors on the left side of the localization space do not transmit localization signals. The resulting transmission schedule thus has the advantage of providing a faster transmission rate for the anchors that cover the right side of the localization space. Similar to FIG. **25**, the transmission order could be alphabetical (i.e., B-C-E-F-H-I-K-L) or more sophisticated (e.g., B-L-E-I-F-H-C-K). It is noted that both of these schedules are uniform in transmission rate, but not uniform in the localization space.

[0264] FIG. **27** shows an illustrative localization system **2700** and a corresponding performance map **2710** in accordance with some embodiments of the present disclosure. Localization system **2700** comprises 5 anchors labelled A to E. The distribution of anchors in localization system **2700** is different than in localization system **2500** of FIG. **25** in that the number of anchors installed on the floor is different than the number of anchors installed on the ceiling. Performance map **2710** indicates that the desired positioning performance is uniform in the localization space.

[0265] In practice, it may be difficult to evenly distribute anchors within a localization space. For example, in some installations, it may be more practical to install a larger number of anchors on the ceiling and a lesser number of anchors on the floor. Localization system **2700** represents such a situation. If all of the anchors of system **2700** transmitted localization signals at the same rate, the positioning performance may be degraded compared to a system that had evenly distributed anchors because 4 out of 5 localization signals will originate from the ceiling. To mitigate the effect of an uneven distribution of anchors, like in localization system **2700**, the transmission schedule can be defined in such a way that the anchor(s) located on the floor transmits more frequently than the ones located on the ceiling. For example, the transmission of localization signals may alternative between the floor and the ceiling such that the transmission rate for localization signals originating from anchors on the floor is the same as the transmission rate for localization signals originating from anchors on the ceiling. For example, one suitable transmission order for localization system **2700** is: A-E-D-E-B-E-C-E. It is noted that this schedule is uniform in space, but not in transmission rate (i.e., different anchors have different transmission rates).

[0266] FIG. **28** shows the illustrative localization system **2500** of FIG. **25** used with a different performance map **2810** in accordance with some embodiments of the present disclosure. Performance map **2810** differs from performance map **2510** of FIG. **25** in that it requires different levels of positioning performance within the localization space. Specifically, the positioning performance in the right part of the localization space is required to be higher than that in the left part of the localization space. For example, performance map **2810** may be used when the majority

of self-localizing apparatuses are in the right part of the localization space. As another example, performance map **2810** may be used when more obstacles are present in the right part of the localization space and thus higher performance is desired to reduce the chance of collision with an obstacle.

[0267] The different levels of positioning performance can be achieved by configuring the anchors in such a way that the anchors covering the left side of the space transmit less frequently than the anchors covering the right side of the space. For example, one suitable transmission order is: B-L-E-I-F-H-C-K-A-L-C-K-D-H-E-G-F-J-B-I, which results in a transmission rate two times faster for the anchors covering the right side of the space. Another suitable transmission order is: B-L-E-I-A-F-H-C-K-J-B-L-E-I-D-F-H-C-K-G, which also results in a transmission rate two times faster for the anchors covering the right side of the space.

[0268] FIG. **29** shows an illustrative transmission schedule **2900** of localization signals in accordance with some embodiments of the present disclosure. Schedule **2900** represents a more sophisticated transmission schedule for localization system **2500** of FIG. **25** that accomplishes the desired positioning performance reflected in performance map **2810** of FIG. **28**. Schedule **2900** comprises 9 rows of information. Row 1 indicates time slots. Rows 2-5 indicate the transmission parameters for a set first set of localization signals that are to be transmitted according to the schedule and rows 6-9 indicate the transmission parameters for a second set of localization signals that are to be transmitted according to the schedule. Rows 2 and 6 identify the anchors. Rows 3 and 7 identify the transmission carrier frequency. Rows 4 and 8 indicate the preamble code. Rows 5 and 9 indicate the transmission power. Accordingly, schedule **2900** differs from the previous exemplary schedules in that it not only specifies the anchor transmission order, but it also specifies additional transmission parameters such as carrier frequency, preamble code, and transmission power. The goal of schedule **2900** is to achieve high performance in the high performance region with little performance impact on the low performance region.

[0269] Schedule **2900** can be considered to have two sub-schedules that are time synchronized. Row 1 shows the time slots in which the sub-schedules are organized. Rows 2-5 can be considered to make up the first sub-schedule, which is the optimized sequence discussed above for FIG. **25**. Rows 6-9 can be considered to make up the second sub-schedule, which defines additional transmissions for the anchors surrounding the high performance region. In this configuration, the first sub-schedule achieves uniform coverage in the entire space and the second sub-schedule increases the positioning performance in the high performance region.

[0270] During time slot T1, anchor A transmits a signal at the same time as anchor E. Because the two anchors transmit on different frequencies, a self-localizing apparatus can select to receive from either anchor A or anchor E to optimize its localization performance based on its position. This can be achieved by having the self-localizing apparatus receive data representative of the possible choices of anchors transmitting at that time slot. The data may be received from a remote location (e.g., as part of a payload of an earlier localization signal) or by using a transmission sequence known in advance and retrieving the data from a memory. The selection can be made in real-time (e.g., by computing the predicted reduction in dilution of precision that could be achieved by receiving either signal) or precomputed (e.g., stored in memory as a map of preferred transceivers based on the current position). A similar selection can be performed during time slots T5 and T10, where two different anchors transmit localization signals on different frequencies.

[0271] During time slot T6, anchor H transmits two signals simultaneously. The second signal is sent out on a frequency different from the first and includes a longer preamble, which allows for the reception of this second signal at greater distance as well as more precise time stamping. The longer preamble of the second signal may cause it to be transmitted during more than one time slot as illustrated. A self-localizing apparatus can thus select to receive signals from anchors H and E transmitted during time slots T6 and T7 on frequency 1, or a more precisely timestampable signal from anchor H transmitted during both time slots T6 and T7 on frequency 2. In this example,

anchor H comprises a pair of transceivers. A similar principle without the need for an anchor having a pair of transceivers is used in time slots T11 and T12.

[0272] During time slot T8, anchor G transmits at the same time as anchor C on the same frequency. In this case, the parameters of anchor C are adjusted such that, to avoid interferences, it transmits at a lower transmission power and can only be received by devices (including self-localizing apparatuses and other anchors) that are out of range of anchor G.

[0273] It will be understood that the schedule depicted in FIG. **29** is merely illustrative and that other variations can be used. In one variation, the first schedule (i.e., rows 2-5) can be changed such that all the transmissions use a longer preamble length to anticipate the transmission of the preambles. For example, an anchor configured to transmit during the time slot T.sub.K could start the transmission of the preamble during the last part of time slot T.sub.K-1. A self-localizing apparatus can thus select to receive the entire preamble or to receive only the part of preamble transmitted during time slot T.sub.K. The first option allows for a more precise timestamping of the localization signal transmitted during time slot T.sub.K while the second option allows the self-localizing apparatus to receive both localization signals.

[0274] FIG. **30** shows another illustrative transmission schedule **3000** of localization signals in accordance with some embodiments of the present disclosure. Schedule **3000** represents another sophisticated transmission schedule. Schedule **3000** specifies even more configuration parameters than set forth in schedule **2900**. Schedule **3000** specifies the transmission time, anchor mode (i.e., reception or transmission), carrier frequency, preamble code, preamble length, transmission power, and antenna used to receive or transmit. Schedule **3000** specifies the configuration parameters of three transceivers (A, B, and C) and is organized in time slots (T1, T2, T3, T4, and T5).

[0275] Anchor A transmits during time slots T1 and T4. Anchor B transmits during time slots T2 and T5. Anchor C transmits during time slot T3. When the anchors are not transmitting, they are configured to receive localization signals transmitted by other anchors.

[0276] Anchor A always operates on frequency F1. Anchor B operates on frequency F1 during time slots T2, T3, and T5, while it operates on frequency F2 during the remaining time slots. Anchor C operates on frequency F1 during time slots T1 and T2, while it operates on frequency F2 during the remaining time slots. Using different frequencies allows for multiple transmissions at the same time (not represented in schedule **3000**).

[0277] Anchor A always uses preamble code 1. Anchor B uses preamble code 5 during time slots T1 and T5, while it uses preamble code 1 during the remaining time slots. Anchor C always uses preamble code 5. Using different preamble codes allows for multiple transmissions at the same time (not represented in schedule **3000**).

[0278] Anchors A and C always transmit localization signals with a preamble length of 250 microseconds. Anchor B always transmits localization signals with a preamble length of 500 microseconds. As mentioned above, a longer preamble length allows for the reception of the localization signal at greater distance as well as with more precise time stamping.

[0279] Anchor A always transmits localization signals with transmission power equal to 5 dBm. Anchors B and C always transmit localization signals with transmission power equal to 0.5 dBm. Using different transmission powers allows for transmissions with longer or shorter coverage. This can be used to have simultaneous but not interfering transmissions from different anchors that use the same frequency and the same preamble code.

[0280] Anchor A always receives and transmits localization signals using antenna 1. Anchor B always transmits using antenna 1 and always receives using antenna 2. Anchor C uses antenna 2 during the first 3 time slots and antenna 1 during the last 2 time slots. Using different antennas allows for transmissions that have different radiation patterns (i.e., can reach different regions of the space with different quality of the signal) and for better reception.

[0281] Self-localizing apparatuses can use the knowledge encoded in the schedule to configure their own reception parameters to receive data from a specific transmitter. A self-localizing

apparatuses can, for example, select to receive a specific signal to optimize its localization performance based on its position.

[0282] In some embodiments, anchors can be configured (as part of schedule **3000**) to receive a specific signal to improve the network clock synchronization or the propagation of information over the network.

[0283] FIG. **31** shows an illustrative flow chart **3100** of logic that may be implemented on a self-localizing apparatus to configure its receiver based on a received payload identifying future transmissions in accordance with some embodiments of the present disclosure.

[0284] At step **3102**, the self-localizing apparatus may read the raw received data from the digital reception electronics upon the reception of a localization signal. Such a read process may be implemented using a digital transmission protocol, for example, SPI, I2C, UART, or a parallel digital protocol.

[0285] At step **3104**, after reading the data, the self-localizing apparatus may decode the received payload. Decoding may include a number of processing steps (not shown). For example, such processing may include: deserialization of data, parsing data representative of payload size, parsing data representative of payload type, any other processing steps, or any combination thereof.

[0286] At decision **3106**, a data integrity check may be performed. For example, a CRC checksum may be verified. If the data integrity check fails (e.g., if the CRC checksum is not correct), the self-localizing apparatus may discard the received data at step **3108** and the process may return to step **3102**. If the integrity check succeeds, the process may proceed to decision **3110**.

[0287] At decision **3110**, the content of the payload may be inspected to determine whether it contains a payload identifying future transmissions by positioning anchors. In some embodiments, step **3110** may be the final step of pre-processing the payload. If the payload is found not to identify future transmissions, the process may be terminated at step **3112** and return to step **3102**. If the payload is found to identify future transmissions by positioning anchors, the process may proceed to decision **3114**.

[0288] At this point, the self-localizing apparatus may carry out steps for determining which of the available localization signals is preferable to receive. For example, this decision may be carried out based on status information provided by the localizer.

[0289] At decision **3114**, the self-localizing apparatus may determine whether the localizer has been successfully initialized (i.e., whether the localizer has a current estimated position). If the self-localizing apparatus determines that that the localizer has not been successfully initialized, the process may proceed to step **3120**. If the self-localizing apparatus determines that that the localizer has been successfully initialized, the process may proceed to step **3116**.

[0290] At step **3120**, when the localizer is not initialized, the self-localizing apparatus may make the decision regarding which signal to receive based on a backup heuristic. For example, the self-localizing apparatus may decide to receive signals that provide the broadest coverage to determine an initial position estimate. The process may then proceed to step **3122**.

[0291] At step **3116**, when the localizer is initialized, the self-localizing apparatus may perform a first check based on the estimated position of the self-localizing apparatus. The position may be compared to the positions of the positioning anchors that will be transmitting signals in future time slots. If for some of these anchors, good reception at the self-localizing apparatus's location will not be possible, then they are marked as non-preferred signals. In some embodiments, this check may additionally account for the orientation of both the anchor antenna and the self-localizing apparatus antenna to more accurately estimate the reception quality. In some embodiments, the metric for what estimated reception quality is deemed acceptable may also be adjusted based on other metrics, for example capturing how important the signal would be for the quality of the position estimate.

[0292] At step **3118**, the localizer's position estimate quality may be inspected. The quality may, for example, be expressed as the current dilution of precision or as the variance of the position estimate. Based on the probable range of positions of the self-localizing apparatus, the reduction of

uncertainty for each of the candidate localization signals may be computed. For example, a simulated version of the future localization signal may be provided to the localizer to evaluate the change in variance. These evaluations may be carried out for each of the candidate localization signals, and a metric may then be applied to determine the preferred localization signal. In some embodiments, such a metric may be the root mean square of the total position variance, the total variance within a plane, or the variance along a direction of particular importance. The process may then proceed to step **3122**.

[0293] After the aforementioned steps are carried out, a preferred localization signal to be received has been determined. At step **3122**, the receiver settings are determined. While the payload may have provided high-level information about the configurations of future localization signals, more low-level receiver settings may typically be required to set up the reception electronics. In some embodiments, these low-level receiver settings may be hardware-dependent settings. For example, the hardware-dependent settings may include at least one of a configuration of phase-locked loops in the reception electronics, the preamble code to scan for during reception, positions of RF switches, other hardware setting, or any combination thereof. In some embodiments, the receiver settings may be stored in a memory in the form of a look-up table, allowing the self-localizing apparatus to determine the correct low-level configuration from the received high-level information.

[0294] At step **3124**, the low-level receiver configuration may be applied to the receiver. In some embodiments, applying the configuration may be performed by writing configuration parameters to registers of the reception electronics through a protocol such as SPI, **12**C, or UART. In some embodiments, applying the configuration may be performed by changing the value of digital or analog input pins of the transmission electronics, for example by changing the state of an output pin of a microcontroller.

[0295] In some embodiments, the status information from the localizer may be used to determine which localization signal to receive. In some embodiments, many other decision criteria may be used for the same purpose. For example, the decision may be made based on a known planned motion of the self-localizing apparatus, based on the signal strength of received localization signals, based on a stored localization signal priority list, based on other criteria, or on any combination thereof.

[0296] It will be understood that the steps and decision elements of flow chart **3100** are merely illustrative and that various modifications can be made within the scope of this disclosure. For example, in some embodiments, the top portion of flow chart **3100** may be performed independently from the bottom portion. For example, logic elements **3102-3112** may be performed on each received signal while logic elements **3114-2124** may separately and repeatedly select what signals to receive. As another example, in some embodiments, logic elements **3102-3112** may not need to be performed when a self-localizing apparatus stores a schedule of which anchors are scheduled to transmit localization signals at which times.

[0297] FIG. **32** shows an illustrative application of a performance map to an indoor and outdoor environment **3200** in which flying operate in accordance with some embodiments of the present disclosure. Environment includes an indoor area within a building **3210** (e.g., a warehouse) with an access area **3220** through which flying machines **3230** can enter and leave the outdoor area. In this example, two localization systems have been installed. One is installed outdoors, while the second is installed indoors.

[0298] The required positioning performance is identified in different areas of the environment. A landing area **3240** surrounds the landing area of flying machines **3230**. Due to tight flight tolerances that may be required during landing, this area is marked as requiring particularly high positioning performance. A second area **3250** covers the majority of the remaining space indoors, and requires a level of localization performance that is sufficient for normal safe flight. The remainder of the indoor space has no localization performance requirements, because the flying

machines do not operate in those spaces.

[0299] A second area requiring particularly high localization performance surrounds access area **3220** that connects the indoor and outdoor areas because the flight maneuvering space is reduced in this area. The remaining outdoor area requires normal localization performance in the approach area to the access area, and no localization performance in other areas.

[0300] Additionally, FIG. **32** shows the availability of other localization mechanisms—in this case, GPS. The availability of such mechanisms may also be provided to the scheduler. If the self-localizing apparatus is configured to fuse different localization systems (such as the systems disclosed herein and GPS) to augment performance, then the scheduler can take this into account and adjust its localization performance requirements to achieve the required total positioning performance under the assumption that the other localization mechanism can be used as a support tool. For example, GPS may provide sufficient positioning performance without the localization systems described herein when flying machines **3230** operate above the building, and the schedule therefore does not need to account for coverage in that area.

[0301] FIG. **32** also shows the application of a bridge anchor, which is used here to allow flying machines to seamlessly transition between the indoor localization system and the outdoor localization system.

[0302] FIG. **33** also shows two illustrative localization networks **3310**, **3320** in accordance with some embodiments of the present disclosure. Localization network **3310** partially overlaps with localization network **3320**. In some embodiments, localization network **3310** comprises a plurality of synchronized anchors and localization network **3320** comprises a plurality of synchronized anchors. However, because localization networks **3310**, **3320** are different networks, they may not be synchronized with respect to each other. Therefore, a self-localizing apparatus may have difficulty in moving between localization networks **3310**, **3320**. To address this problem, one or more bridge anchors may be used to enable a self-localizing apparatus to switch from one network to the other. As illustrated, two bridge anchors **3330** are located in the area of overlap between the two networks.

[0303] FIG. **34** is a block diagram of an illustrative bridge anchor that is configured to allow the synchronization of two localization systems (e.g., localization networks **3310**, **3320**) in accordance with some embodiments of the present disclosure. When two separate localization systems are used in the vicinity of each other, self-localizing apparatus that switch from receiving signals of the first system to receiving signals of the second system (e.g., because they moved from a location where the first system provides better performance to one where the second system provides better performance) would normally be required to re-initialize their localization unit to identify the timing information of the second localization system and then determine its position again. This would produce a black-out period during which no (or only degraded) localization is available as the self-localizing apparatus switches from one network to the next. The bridge transceiver shown in FIG. **34** allows the synchronization of the timing information between two neighboring networks, such that a self-localizing apparatus is able to switch between networks while keeping its local timing information as if it was still receiving localizing signals from the first network.

[0304] Like some of the anchors disclosed herein, this bridge anchor contains a clock **210**, a scheduling unit **218***a*, digital transmission electronics **216***a*, analog transmission electronics **214***a*, antenna **212***a*, analog reception electronics **220***a*, and digital reception electronics **222***a*. These components are used for the bridge anchor to communicate with, and provide localization signals on, the first localization system.

[0305] To enable the bridge functionality, the bridge anchor in this embodiment includes a second set of some of the components used for the first localization system. Specifically, the bridge anchor here additionally includes scheduling unit **218***b*, digital transmission electronics **216***b*, analog transmission electronics **214***b*, antenna **212***b*, analog reception electronics **220***b*, and digital reception electronics **224***b*. These additional components are configured to receive and transmit

signals of the second localization system.

[0306] The bridge anchor in this embodiment also includes synchronization unit **224***a* coupled to digital reception electronics **222***a* and clock **210**. Synchronization unit **224***a* determines timing information of the first localization system. The bridge anchor here also includes a synchronization unit **224***b* to likewise determine timing information of the second localization system. In addition, synchronization unit **224***b* receives timing information of synchronization unit **224***a* to compare the timing information from the two localization systems. Synchronization unit **224***b* is coupled to scheduling unit **218***b* and can adjust the scheduling operation of the second localization system by at least one of (1) adjusting the scheduling of the second localization system such that it is steered towards being in synchrony with the scheduling of the first localization system and (2) including information in the transmission payload that causes the anchors in the second localization system to adjust their timing to the first localization system. The timing information referred to in this context could, for example, be the apparent clock rate of the localization system, the apparent clock offset, or the apparent clock skew.

[0307] FIG. **35** is a block diagram of another illustrative bridge anchor that is configured to enable seamless transition of a self-localizing apparatus from one localization system to another in accordance with some embodiments of the present disclosure. Unlike the bridge anchor of FIG. **34**, the bridge anchor of FIG. **35** does not share common timing information between two localization systems to synchronize them to each other. Therefore, the bridge anchor of FIG. **35** is required to enable seamless transition between two unsynchronized localization systems. The difficulty that causes a self-localization apparatus to have temporarily unavailable (or reduced performance) localization is that, to provide meaningful localization data, the self-localization apparatus needs to identify the timing of the second localization system when the localizer is reinitialized. The bridge transceiver shown in FIG. **35** allows the self-localization apparatus to quickly switch from a first to a second localization system by hot-starting its localizer after re-initialization, using additional timing information from the second localization system.

[0308] To achieve this, the bridge transceiver of FIG. **35** includes analog reception electronics **220** and digital reception electronics **222**, coupled to antenna **212**, which receives signals from the second localization system. Digital transmission electronics **216** and analog transmission electronics **214** are configured to transmit signals with the configuration of the first localization system. The reception and transmission electronics share a clock **210**. The signals received from digital reception electronics **222** are provided to synchronization unit **224**, which identifies the timing information of the received signals (which are signals from the second localization system). The identified timing information is sent to scheduling unit **218**, which can include the identified timing information in the payload transmitted on the first localization system. A self-localizing apparatus receiving signals from the first localization system can decode this timing information and may, as it switches from the first to the second localization system, use the timing information to hot-start the localizer for the second localization system.

[0309] According to one aspect of the present disclosure, a localization system is provided that comprises a plurality of positioning anchors configured to wirelessly transmit localization signals. The localization signals may be capable of being used by self-localizing apparatus within a region to determine position information. For example, a self-localizing apparatus may use the localization signals to determine its own position within a defined three dimensional region.

[0310] In some embodiments, the plurality of the positioning anchors may comprise a first positioning anchor, a second positioning anchor, and a third positioning anchor. The first positioning anchor may be configured to wirelessly transmit first localization signals. The second positioning anchor may be configured to wirelessly transmit second localization signals. The third positioning anchor may be configured to wirelessly transmit third localization signals.

[0311] In some embodiments, each of the plurality of positioning anchors may be communicatively coupled to a scheduling unit. In some embodiments, the scheduling unit may be configured to

schedule the transmission of the localization signals. For example, the scheduling unit may schedule the transmission of the first localization signals, second localization signals, and third localization signals. In some embodiments, the scheduling unit may schedule the transmission of the localization signals to control positioning performance. For example, the scheduling unit may schedule the first positioning anchor to transmit the first localization signals at a first transmission rate, schedule the second positioning anchor to transmit the second localization signals at a second transmission rate, and schedule the third positioning anchor to transmit the third localization signals at a third transmission rate. In some embodiments, the first transmission rate may be greater than the second transmission rate. In some embodiments, the first transmission rate, the second transmission rate, and the third transmission rates may be selected to provide greater positioning performance within a portion of the region.

[0312] In some embodiments, the scheduling unit may be configured to adjust the transmission rate of either of the first, second, and third localization signals, or any combination thereof in order to change the positioning performance within the region during operation. In some embodiments, the scheduling unit may be configured to receive location of the self-localizing apparatus and/or the flight pattern of the self-localizing apparatus. In some embodiments, the scheduling unit may be configured to adjust the transmission rates based on a known location of the self-localizing apparatus. In some embodiments, the scheduling unit may be configured to adjust the transmission rates based on a known motion of the self-localizing apparatus (e.g., a flight pattern).

[0313] In some embodiments, each of the first, second, and third localization signals may comprise ultra-wideband (UWB) localization signals. Each of the UWB localization signals may comprise a preamble code and a payload. In some embodiments, some of the UWB localization signals may comprise a payload that comprises commands. In some embodiments, the scheduling unit may be configured to schedule the transmission of the UWB localization signals to optimize the propagation of the commands to at least one of a self-localizing apparatus and the plurality of the anchors.

[0314] In some embodiments, each of the plurality of positioning anchors may comprise a clock. In some embodiments, some of the UWB localization signals may comprise a payload that comprises synchronization data. Each of the plurality of positioning anchors may be configured to receive the synchronization data from UWB localization signals received from at least one other positioning anchor. In some embodiments, the at least one scheduling unit may be configured to schedule the transmission of the UWB localization signals to optimize the synchronization of the clocks.

[0315] In some embodiments, the optimization for the synchronization of the clocks may be performed by including an objective function or a constraint that may representative of the clock synchronization performance. For example, such an optimization may incorporate a model that predicts the timestamping variability in dependence of environmental effects, with the objective being to achieve high communication rates between anchors that have low timestamping variability.

[0316] In some embodiments, each of the plurality of positioning anchors may comprise a synchronization unit, wherein each synchronization unit may be configured to compute a correction for at least one of a clock offset and a clock rate for its respective clock based on the received synchronization data.

[0317] In some embodiments, the scheduling unit may be configured to schedule the transmission of the localization signals to increase at least one of precision, accuracy, or update rate in one or more portions of the region. In some embodiments, the scheduling unit may be configured to schedule the transmission of the localization signals based on time slots in a schedule. In some embodiments, the first positioning anchor may be assigned more time slots in the schedule than the second positioning anchor.

[0318] In some embodiments, the scheduling unit may comprise a first scheduling unit, a second scheduling unit, and a third scheduling unit. The first scheduling unit may be physically coupled to

the first positioning anchor and may be configured to schedule the transmission of the first localization signals. The second scheduling unit may be physically coupled to the second positioning anchor and may be configured to schedule the transmission of the second localization signals. The third scheduling unit may be physically coupled to the third positioning anchor and may be configured to schedule the transmission of the third localization signals.

[0319] In some embodiments, a method for transmitting localization signals in a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors.

[0320] In some embodiments, the method may comprise a first positioning anchor of the plurality of positioning anchors wirelessly transmitting first localization signals during two or more time slots of a transmission schedule. The method may further comprise a second positioning anchor of the plurality of positioning anchors wirelessly transmitting second localization signals during one or more time slots of the transmission schedule. The method may further comprise a third positioning anchor of the plurality of positioning anchors wirelessly transmitting third localization signals during one or more time slots of the transmission schedule.

[0321] In some embodiments, the first localization signals, the second localization signals, and the third localization signals may be capable of being used by self-localizing apparatus within a region to determine position information. The first positioning anchor may be assigned more time slots in the transmission schedule than the second positioning anchor to provide greater positioning performance within a portion of the region.

[0322] In some embodiments, the method may comprise one or more scheduling units adjusting the number of time slots the first positioning anchor, the second positioning anchor, and the third positioning anchor are assigned in the transmission schedule during operation. In some embodiments, the method may comprise wirelessly receiving the known location of the self-localizing apparatus. In some embodiments, the number of time slots may be adjusted based on a known location of the self-localizing apparatus.

[0323] In some embodiments, the time slots of the transmission schedule may be assigned based on one or more of: a known location of the self-localizing apparatus; optimization of propagation of commands comprised as part of at least some of the first, second, and third localization signals; optimization of synchronization of clocks associated with the first, second, and third positioning anchors, and at least one of improved precision, accuracy, or update rate in one or more portions of the region.

[0324] In some embodiments, the method may further comprise generating, using a first clock, first timing signals used to determine when the first positioning anchor wirelessly transmits the first localization signals. The method may further comprise generating, using a second clock, second timing signals used to determine when the second positioning anchor wirelessly transmits the second localization signals. The method may further comprise generating, using a third clock, a third timing signal used to determine when the third positioning anchor wirelessly transmits the third localization signals, wherein the first, second, and third clocks are synchronized.

[0325] According to another aspect of the present disclosure, a localization system is provided that comprises a plurality of positioning anchors that may be configured to wirelessly transmit localization signals capable of being used by self-localizing apparatus within a region to determine position information. In some embodiments, the region may comprise a three-dimensional region.

[0326] In some embodiments, the localization system may further comprise at least one scheduling unit. The at least one scheduling unit may be communicatively coupled to the plurality of positioning anchors. In some embodiments, the at least one scheduling unit may be configured to schedule the transmission of the localization signals according to a first transmission schedule. The first transmission schedule may define a first temporal order for each of the plurality of positioning anchors to transmit the localization signals. In some embodiments, the localization signals may comprise ultra-wideband (UWB) localization signals. In some embodiments, each of the

localization signals may comprise a preamble code and a payload.

[0327] In some embodiments, the at least one scheduling unit may be configured to determine when to change from the first transmission schedule to a second transmission schedule. The second transmission schedule may define a second temporal order for each of the plurality of positioning anchors to transmit localization signals. The second transmission schedule may define a second transmitter (TX) or receiver (RX) mode for each of the plurality of positioning anchors. In some embodiments, the second temporal order may be different than the first temporal order. In some embodiments, the second temporal order may be identical to the first temporal order.

[0328] In some embodiments, the at least one scheduling unit may be configured to determine when to restart a transmission schedule. In some embodiments, the at least one scheduling unit may be configured to start or restart a transmission schedule from a specific time (i.e., the schedule does not start or restart from the schedule's beginning). In some embodiments, the first transmission schedule and the second transmission schedule may provide at least one of increased precision, accuracy, and update rate in different portions of the region.

[0329] In some embodiments, the at least one scheduling unit may be configured to schedule, in response to a determination to change from the first transmission schedule to the second transmission schedule, the transmission of the localization signals according to the second transmission schedule. In some embodiments, the change from the first transmission schedule to the second transmission schedule may change the positioning performance within the region.

[0330] In some embodiments, the at least one scheduling unit may be configured to receive the known location of the self-localizing apparatus and/or a flight pattern of the self-localizing apparatus. In some embodiments, the at least one scheduling unit may be configured to determine when to change from the first transmission schedule to a second transmission schedule based on a known location of the self-localizing apparatus. In some embodiments, the at least one scheduling unit may be configured to determine when to change from the first transmission schedule to a second transmission schedule based on user input. In some embodiments, the at least one scheduling unit may be configured to determine when to change from the first transmission schedule to a second transmission schedule based on a known motion of the self-localizing apparatus.

[0331] In some embodiments, the payload of at least some of the UWB localization signals may comprise commands. In some embodiments, the at least one scheduling unit may be configured to change from the first transmission schedule to the second transmission schedule to optimize the propagation of the commands to at least one of a self-localizing apparatus and the plurality of the anchors.

[0332] In some embodiments, each of the plurality of positioning anchors may comprise a clock. In some embodiments, the payload of at least some of the UWB localization signals may comprise synchronization data. Each of the plurality of positioning anchors may be configured to receive the synchronization data from UWB localization signals received from at least one other positioning anchor. The at least one scheduling unit may be configured to change from the first transmission schedule to the second transmission schedule to optimize for the synchronization of the clocks.

[0333] In some embodiments, each of the plurality of positioning anchors may comprise a synchronization unit. Each synchronization unit may be configured to compute a correction for at least one of a clock offset and a clock rate for its respective clock based on the received synchronization data.

[0334] In some embodiments, the first transmission schedule and the second transmission schedule may each comprise a plurality of time slots. In some embodiments, at least one positioning anchor of the plurality of positioning anchors may be assigned a different number of time slots in the first transmission schedule and the second transmission schedule. In some embodiments, at least one positioning anchor of the plurality of positioning anchors may be assigned a different transmitter (TX) mode or receiver (RX) mode. In some embodiments, at least one positioning anchor of the

plurality of positioning anchors may be assigned a different transmitter (TX) mode or receiver (RX) mode in the first transmission schedule and the second transmission schedule.

[0335] In some embodiments, the at least one scheduling unit may comprise a plurality of scheduling units. In some embodiments, each of the plurality of scheduling units may be physically coupled to a respective one of the plurality of positioning anchors. In some embodiments, each of the plurality of scheduling units may be configured to schedule the transmission of localization signals for its respective positioning anchor according to the time slots assigned to its respective positioning anchor.

[0336] In some embodiments, a method for transmitting localization signals in a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors.

[0337] In some embodiments, the method may comprise using the plurality of positioning anchors to wirelessly transmit localization signals capable of being used by self-localizing apparatus within a region to determine position information. In some embodiments, the method may further comprise using at least one scheduling unit communicatively coupled to the plurality of positioning anchors to schedule the transmission of the localization signals according to a first transmission schedule. In some embodiments, the first transmission schedule may define a first temporal order for each of the plurality of positioning anchors to transmit the localization signals.

[0338] In some embodiments, the method may further comprise using the at least one scheduling unit to determine when to change from the first transmission schedule to a second transmission schedule. In some embodiments, the second transmission schedule may define a second temporal order for each of the plurality of positioning anchors to transmit localization signals. The second transmission schedule may define a second transmitter (TX) or receiver (RX) mode for each of the plurality of positioning anchors. In some embodiments, the second temporal order may be different than the first temporal order.

[0339] In some embodiments, the method may further comprise using the at least one scheduling unit to schedule, in response to a determination to change from the first transmission schedule to the second transmission schedule, the transmission of the localization signals according to the second transmission schedule. In some embodiments, such scheduling may change the positioning performance within the region.

[0340] In some embodiments, the localization signals may comprise ultra-wideband (UWB) localization signals. In some embodiments, each localization signal may comprise a preamble code and a payload. In some embodiments, the payload of at least some of the UWB localization signals may comprise commands. In some embodiments, the method may further comprise changing the at least one scheduling unit from the first transmission schedule to the second transmission schedule to optimize the propagation of the commands to at least one of a self-localizing apparatus and the plurality of the anchors.

[0341] In some embodiments, each of the plurality of positioning anchors may comprise a clock. In some embodiments, the payload of at least some of the UWB localization signals may comprise synchronization data. In some embodiments, the method may further comprise using each of the plurality of positioning anchors to receive synchronization data from UWB localization signals from at least one other positioning anchor. In some embodiments, the method may further comprise changing the at least one scheduling unit from the first transmission schedule to the second transmission schedule to optimize for the synchronization of the clocks.

[0342] In some embodiments, each of the plurality of positioning anchors may comprise a synchronization unit. In some embodiments, the method may further comprise using each synchronization unit to compute, a correction for at least one of a clock offset and a clock rate for its respective clock based on the received synchronization data.

[0343] In some embodiments, the first transmission schedule and the second transmission schedule may provide at least one of increased precision, accuracy, and update rate in different portions of

the region.

[0344] In some embodiments, the first transmission schedule and the second transmission schedule may each comprise a plurality of time slots. In some embodiments, the method may further comprise assigning a different number of time slots in the first transmission schedule and the second transmission schedule to at least one positioning anchor of the plurality of positioning anchors.

[0345] In some embodiments, the first transmission schedule and the second transmission schedule may each comprise a plurality of time slots. In some embodiments, the at least one scheduling unit may comprise a plurality of scheduling units. In some embodiments, each of the plurality of schedule units may be physically coupled to a respective one of the plurality of positioning anchors. In some embodiments, the method may further comprise using each of the plurality of scheduling units to schedule the transmission of localization signals for its respective positioning anchor according to the time slots assigned to its respective positioning anchor.

[0346] According to another aspect of the present disclosure, a system for determining a transmission schedule for a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors configured to wirelessly transmit localization signals. The plurality of positioning anchors may be used for determining position information within a region.

[0347] In some embodiments, the system may comprise an input. The input may be operable to receive: locations of the plurality of positioning anchors, at least one anchor property of the plurality of positioning anchors, and desired positioning performance within at least one zone within the region.

[0348] In some embodiments, the system may comprise at least one processor. The at least one processor may be configured to determine the transmission schedule for the plurality of anchors based on (a) the locations of the plurality of positioning anchors, (b) the at least one anchor property of the plurality of positioning anchors, and (c) the desired positioning performance within the at least one zone. In some embodiments, the plurality of positioning anchors may be configured to wirelessly transmit the localization signals according to the transmission schedule.

[0349] In some embodiments, the system may comprise an output operable to communicate the transmission schedule to the plurality of positioning anchors.

[0350] In some embodiments, the desired positioning performance within a first of the at least one zone may be greater than the desired positioning performance within a second of the at least one zone. In some embodiments, the determined transmission schedule may be determined to provide greater positioning performance within the first zone. In some embodiments, the at least one zone may cover the region.

[0351] In some embodiments, the at least one processor may be configured to determine the transmission schedule by predicting positioning performance within the at least one zone based on the locations of the plurality of positioning anchors and the at least one anchor property of the plurality of positioning anchors; and comparing the predicted positioning performance to the desired positioning performance within the at least one zone.

[0352] In some embodiments, the at least one anchor property may comprise transmission power levels. In some embodiments, the at least one processor may be further configured to determine transmission power levels for the transmission schedule. In some embodiments, the transmission schedule may indicates the power level each positioning anchor may be scheduled to use for transmitting its localization signals.

[0353] In some embodiments, the at least one anchor property may comprise transmission center frequencies. In some embodiments, the at least one processor may be further configured to determine transmission center frequencies for the transmission schedule. In some embodiments, the transmission schedule may indicates the transmission center frequency each positioning anchor may be scheduled to use for transmitting its localization signals.

[0354] In some embodiments, the at least one anchor property may comprise transmission frequency bandwidths. In some embodiments, the at least one processor may be further configured to determine transmission frequency bandwidths for the transmission schedule. In some embodiments, the transmission schedule may indicate the transmission frequency bandwidth each positioning anchor may be scheduled to use for transmitting its localization signals.

[0355] In some embodiments, the at least one anchor property may comprise preamble codes. In some embodiments, the at least one processor may be further configured to determine preamble codes for the transmission schedule. In some embodiments, the transmission schedule may indicate the preamble code scheduled to be used with each localization signal.

[0356] In some embodiments, the at least one anchor property may comprise preamble modulation schemes. In some embodiments, the at least one processor may be further configured to determine the preamble modulation schemes for the transmission schedule. In some embodiments, the transmission schedule may indicate the preamble modulation scheme scheduled to be used with each localization signal.

[0357] In some embodiments, the at least one anchor property may comprise preamble length. In some embodiments, the at least one processor may be further configured to determine the preamble lengths for the transmission schedule. In some embodiments, the transmission schedule may indicate the preamble lengths scheduled to be used with each localization signal.

[0358] In some embodiments, the transmission schedule may comprise a plurality of time slots. In some embodiments, the at least one processor may be further configured to assign one or more localization signals to each of the plurality of time slots.

[0359] In some embodiments, the at least one processor may be further configured to determine an amount of overlap of the plurality of time slots of the transmission schedule. In some embodiments, the amount of overlap of the plurality of time slots may be fixed. In some embodiments, the amount of overlap of the plurality of time slots may be variable. In some embodiments, the at least one processor may be configured to determine the transmission schedule by determining a temporal order for the plurality of positioning anchors to wirelessly transmit the localization signals.

[0360] In some embodiments, the at least one processor may be configured to determine the transmission schedule by determining transmission rates for the plurality of positioning anchors to wirelessly transmit the localization signals.

[0361] In some embodiments, the transmission schedule may comprise a plurality of time slots. In some embodiments, the at least one processor may be further configured to assign more time slots to a positioning anchor with a higher transmission rate than to a positioning anchor with a lower transmission rate.

[0362] In some embodiments, the at least one processor may be configured to determine the transmission schedule by using an optimization algorithm. In some embodiments, the at least one processor may be configured to determine the transmission schedule by minimizing a cost function.

[0363] In some embodiments, the input may be further operable to receive real-time positioning information of self-localizing apparatus within the region. In some embodiments, the at least one processor may be further configured to determine an updated transmission schedule based on the real-time positioning information. In some embodiments, the real-time positioning information may be received from memory of the system. In some embodiments, the desired positioning performance nay comprises a flight pattern.

[0364] In some embodiments, a method for determining a transmission schedule for a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors configured to wirelessly transmit localization signals that may be used for determining position information within a region.

[0365] In some embodiments, the method may comprise using an input to receive locations of the plurality of positioning anchors, at least one anchor property of the plurality of positioning anchors, and desired positioning performance within at least one zone within the region.

[0366] In some embodiments, the method may further comprise using at least one processor to determine the transmission schedule for the plurality of anchors based on (a) the locations of the plurality of positioning anchors, (b) the at least one anchor property of the plurality of positioning anchors, and (c) the desired positioning performance within the at least one zone, wherein the plurality of positioning anchors are configured to wirelessly transmit the localization signals according to the transmission schedule. In some embodiments, the method may further comprise using an output to communicate the transmission schedule to the plurality of positioning anchors.

[0367] In some embodiments, the method may further comprise using the at least one processor to predict positioning performance within the at least one zone based on the locations of the plurality of positioning anchors and the at least one anchor property of the plurality of positioning anchors. The method may further comprise using the at least one processor to compare the predicted positioning performance to the desired positioning performance within the at least one zone.

[0368] In some embodiments, the at least one anchor property may comprise transmission power levels. The method may further comprise using at least one processor to determine transmission power levels for the transmission schedule. In some embodiments, the transmission schedule may indicate the power level each positioning anchor may be scheduled to use for transmitting its localization signals.

[0369] According to another aspect of the present disclosure, a localization system may comprise a plurality of positioning anchors configured to wirelessly transmit localization signals during time slots of a transmission schedule. In some embodiments, each localization signal may comprise a payload. In some embodiments, the payload for each localization signal may identify at least one positioning anchor of the plurality of positioning anchors configured to transmit a localization signal during at least one future time slot.

[0370] In some embodiments, a localization system may comprise a plurality of positioning anchors configured to wirelessly transmit wireless signals during time slots of a transmission schedule. In some embodiments, each wireless signal may comprise a payload. In some embodiments, the payload for each wireless signal may identify a configuration for a transmitter (TX) mode or a configuration for a receiver (RX) mode of at least one positioning anchor of the plurality of positioning anchors configured to transmit or receive a localization or wireless signal during at least one future time slot. In some embodiments, the payload may only identify a configuration for a TX mode and the anchor may determine its RX modes.

[0371] In some embodiments, the localization system may comprise a self-localizing apparatus. In some embodiments, the self-localizing apparatus may comprise a receiver. The self-localizing apparatus may be configured to receive at least some of the localization signal, extract the payload of the received localization signals. The self-localizing apparatus may be further configured to determine, based on the extracted payload of the received localization signals, which localization signals to receive for determining positioning information of the self-localizing apparatus. The self-localizing apparatus may be configured to configure the receiver based on the determined localization signals. The self-localizing apparatus may be further configured to receive, using the configured receiver, the determined localization signals, and determine the positioning information of the self-localizing apparatus based on the received determined localization signals.

[0372] In some embodiments, each localization signal may comprise a header portion and a payload portion. In some embodiments, the header portion may be a preamble. In some embodiments, the localization signals may comprise a first subgroup and a second subgroup. In some embodiments, the first subgroup and the second subgroup may comprise at least one different transmission characteristic. In some embodiments, the at least one different transmission characteristic may comprise at least one of transmission center frequency, transmission frequency bandwidth, preamble code, and preamble modulation scheme. In some embodiments, a localization signal from the first subgroup and a localization signal from the second subgroup may both be scheduled for transmission during the same time slot of the transmission schedule.

[0373] In some embodiments, the self-localizing apparatus may be configured to determine which localization signals to receive based on status information. In some embodiments, the status information may comprise a current position of the self-localizing apparatus. In some embodiments, the status information may comprise variance information associated with a localization estimator of the self-localizing apparatus.

[0374] In some embodiments, the self-localizing apparatus may be configured to determine which localization signals to receive to minimize variance associated with the localization estimator.

[0375] In some embodiments, the payload for each localization signal may identify two positioning anchors of the plurality of positioning anchors configured to transmit localization signals during the same future time slot. In some embodiments, the payload for each localization signal may identify at least one positioning anchor of the plurality of positioning anchors configured to transmit a localization signal during each of at least two future time slots.

[0376] In some embodiments, a localization method is provided. The method may comprise using a plurality of positioning anchors to wirelessly transmit localization signals during time slots of a transmission schedule. In some embodiments, each localization signal may comprise a payload. In some embodiments, the payload for each localization signal may identify at least one positioning anchor of the plurality of positioning anchors configured to transmit a localization signal during at least one future time slot.

[0377] The method may comprise using a self-localizing apparatus to receive at least some of the localization signals, extract the payload of the received localization signals, and determine which localization signals to receive for determining positioning information of the self-localizing apparatus based on the extracted payload of the received localization signals. In some embodiments, the method may comprise configuring the receiver of the self-localizing apparatus based on the determined localization signals. In some embodiments, the method may further comprise using the configured receiver to receive the determined localization signals, and determine the positioning information.

[0378] In some embodiments, the localization signals may comprise a first subgroup and a second subgroup, wherein the first subgroup and the second subgroup comprise at least one different transmission characteristic.

[0379] In some embodiments, the at least one different transmission characteristic comprises at least one of transmission center frequency, transmission frequency bandwidth, preamble code, and preamble modulation scheme. In some embodiments, a localization signal from the first subgroup and a localization signal from the second subgroup may both be scheduled for transmission during the same time slot of the transmission schedule.

[0380] In some embodiments, the method may further comprise using the self-localizing apparatus to determine which localization signals to receive based on status information. In some embodiments, the status information may comprise current position of the self-localizing apparatus. In some embodiments, the status information nay comprise variance information associated with a localization estimator of the self-localizing apparatus.

[0381] In some embodiments, the method may further comprise using the self-localizing apparatus to determine which localization signals to receive to minimize variance associated with the localization estimator.

[0382] In some embodiments, the payload for each localization signal may identify two positioning anchors of the plurality of positioning anchors configured to transmit localization signals during the same future time slot. In some embodiments, the payload for each localization signal may identify at least one positioning anchor of the plurality of positioning anchors configured to transmit a localization signal during each of at least two future time slots.

[0383] According to another aspect of the present disclosure, a localization system is provided that comprises a first localization network configured to wirelessly transmit first localization signals using a first set of time synchronized anchors. In some embodiments, the first localization signals

may be usable to determine position information within a first region.

[0384] In some embodiments, the localization system may further comprise a second localization network configured to wirelessly transmit second localization signals using a second set of time synchronized anchors. In some embodiments, the second localization signals may be usable to determine position information within a second region.

[0385] In some embodiments, the localization system may further comprise a bridge anchor. In some embodiments, the bridge anchor may be configured to receive first time synchronization information related to the first set of time synchronized anchors. The bridge anchor may be configured to receive second time synchronization information related to the second set of time synchronized anchors, transmit time synchronization information related to the first time synchronization information to the second localization network. In some embodiments, the time synchronization information may comprise at least one of a clock offset and a clock rate of the first localization network.

[0386] In some embodiments, the second localization network may be configured to adjust at least one of a clock offset and a clock rate based on the received time synchronization information to time synchronize the second localization network with the first localization network.

[0387] In some embodiments, the bridge anchor may be configured to transmit the time synchronization information wirelessly. In some embodiments, wherein at least one anchor of the second localization network may be configured to wirelessly receive the time synchronization information.

[0388] In some embodiments, the bridge anchor may be further configured to transmit time synchronization information related to the second time synchronization information to the first localization network.

[0389] In some embodiments, the bridge anchor may be configured to transmit the time synchronization information wirelessly to a self-localizing apparatus of the first localization network to enable the self-localizing apparatus to determine its position using the first localization network and second localization network.

[0390] In some embodiments, the self-localizing apparatus may be configured to switch between receiving localization signals from the first localization network and localization signals from the second localization network based on the received time synchronization information. In some embodiments, the switching may be achieved by reconfiguring the receiver of the self-localizing apparatus. In some embodiments, the signals transmitted by the bridge anchor may comprise a payload representative of the receiver configuration for at least one of the two localization networks. In some embodiments, the self-localizing apparatus may reconfigure its receiver based on the payload received from the bridge anchor.

[0391] In some embodiments, the bridge anchor may be further configured to wirelessly transmit one or more of the second localization signals. In some embodiments, the one or more of the second localization signals may each comprise a preamble and a payload. In some embodiments, the payload of the one or more of the second localization signals may comprise the time synchronization information.

[0392] In some embodiments, the localization system of claim may further comprising a self-localizing apparatus. In some embodiments, the self-localizing apparatus may be configured to receive the second localization signals, and determine position information based on the received second localization signals. In some embodiments, the self-localizing apparatus may be configured to configure its receiver to receive the first localization signals, and determine position information based on the received first localization signals.

[0393] In some embodiments, the self-localizing apparatus may be further configured to receive time synchronization information from the bridge anchor. In some embodiments, the determining position information may be based on the received first localization signals may be further carried out in dependence of the time synchronization information from the bridge anchor.

[0394] In some embodiments, the self-localizing apparatus may be configured to receive one or more of the first localization signals from the first localization network, receive the one or more of the second localization signals from the bridge anchor, and receive one or more of the second localization signals from the second localization network. In some embodiments, the self-localizing apparatus may be further configured to determine position information based on the one or more first localization signals received from the first localization network, the one or more of the second localization signals received from the second localization network, and the time synchronization information received from the bridge anchor.

[0395] In some embodiments, the bridge anchor may be configured to alternately receive localization signals from the first localization network and the second localization network. In some embodiments, the first region and the second region at least partially overlap.

[0396] In some embodiments, the bridge anchor may configured to determine relative time information based on the received first time synchronization information and the received second time synchronization information and wherein the time synchronization information transmitted by the bridge anchor comprises the relative time information.

[0397] In some embodiments, the localization system may comprise a first localization network configured to transmit first localization signals using a first set of time synchronized anchors. In some embodiments, the first localization signals are usable to determine position information within a first region.

[0398] In some embodiments, the localization system may comprise a second localization network configured to transmit second localization signals using a second set of time synchronized anchors. In some embodiments, the second localization signals are usable to determine position information within a second region. In some embodiments, the localization system may comprise a bridge anchor.

[0399] In some embodiments, the bridge anchor may be configured to receive first time synchronization information related to the first set of time synchronized anchors, and to receive second time synchronization information related to the second set of time synchronized anchors. In some embodiments, the bridge anchor may be configured to transmit first localization signals based the received first time synchronization information as part of the first localization network in a first mode of operation; and to transmit second localization signals based the received second time synchronization information as part of the second localization network in a second mode of operation.

[0400] In some embodiments, the bridge anchor may be configured to switch between the first mode of operation and the second mode of operation based on desired positioning performance of at least one of the first and second localization networks.

[0401] In some embodiments, a localization method is provided. In some embodiments, the localization method may comprise using a first localization network to wirelessly transmit first localization signals using a first set of time synchronized anchors. The first localization signals may be usable to determine position information within a first region.

[0402] In some embodiments, the localization method may comprise using a second localization network to wirelessly transmit second localization signals using a second set of time synchronized anchors. The second localization signals may be usable to determine position information within a second region.

[0403] In some embodiments, the localization method may further comprise using a bridge anchor to receive first time synchronization information related to the first set of time synchronized anchors, and to receive second time synchronization information related to the second set of time synchronized anchors. The localization method may further comprise using a bridge anchor to transmit time synchronization information related to the first time synchronization information to the second localization network.

[0404] In some embodiments, the localization method may further comprise using the bridge

anchor to transmit the time synchronization information wirelessly to a self-localizing apparatus of the first localization network to enable the self-localizing apparatus to determine its position using the first localization network and second localization network.

[0405] In some embodiments, another localization method is provided. In some embodiments, the localization method may comprise using a first localization network to transmit first localization signals using a first set of time synchronized anchors. The first localization signals may be usable to determine position information within a first region.

[0406] In some embodiments, the localization method may also comprise using a second localization network to transmit second localization signals using a second set of time synchronized anchors. The second localization signals may be usable to determine position information within a second region.

[0407] In some embodiments, the localization method may further comprise using a bridge anchor to receive first time synchronization information related to the first set of time synchronized anchors, and to receive second time synchronization information related to the second set of time synchronized anchors.

[0408] In some embodiments, the localization method may also comprise using the bridge anchor to wirelessly transmit first localization signals based the received first time synchronization information as part of the first localization network in a first mode of operation, and transmitting second localization signals based the received second time synchronization information as part of the second localization network in a second mode of operation.

[0409] According to another aspect of the present disclosure, a localization system is provided that comprises a first anchor configured to transmit a first timestampable localization signal. In some embodiments, the first timestampable localization signal comprise a preamble followed by a payload.

[0410] The localization system may further comprise a second anchor configured to transmit a second timestampable localization signal. In some embodiments, the second timestampable localization signal may comprise a preamble followed by a payload. In some embodiments, the transmission of the second timestampable localization signal may partially overlap with the transmission of the first timestampable localization signal such that the second timestampable localization signal does not overlap the preamble of the first timestampable localization signal. In some embodiments, the first timestampable localization signal and the second timestampable localization signal may be received within a common region.

[0411] In some embodiments, transmission of the second timestampable localization signal may begin before the transmission of first timestampable localization signal ends. In some embodiments, the transmission of the second timestampable localization signal may begin after the transmission of the first timestampable localization signal's preamble ends. In some embodiments, the preamble of the second timestampable localization signal may overlap with the payload of the first timestampable localization signal.

[0412] In some embodiments, the preamble of the first timestampable localization signal may comprise a first coded preamble. In some embodiments, the preamble of the second timestampable localization signal may comprise a second, identically coded preamble.

[0413] In some embodiments, the localization system may comprise a self-localizing apparatus. In some embodiments, the self-localizing apparatus may be configured to receive the entire first timestampable localization signal or the entire second timestampable localization signal, but not the entire first timestampable localization signal and the entire second timestampable localization signal. In some embodiments, the self-localizing apparatus may be configured to receive the preamble of the first timestampable localization signal and the entire second timestampable localization signal.

[0414] In some embodiments, the first timestampable localization signal may further comprise a start of frame delimiter (SFD) between the preamble and the payload. In some embodiments, the

second timestampable localization signal may not overlap the SFD of the first timestampable localization signal. In some embodiments, the self-localizing apparatus may be configured to receive the preamble and the SFD of the first timestampable localization signal and the entire second timestampable localization signal.

[0415] In some embodiments, the self-localizing apparatus may be further configured to determine a timestamp corresponding to the reception of the preamble or the SFD of the first localization signal; and determine position information based on a known transmission time of the first timestampable localization signal and the timestamp.

[0416] In some embodiments, the payload of the first timestampable localization signal may comprise first and second payloads. In some embodiments, the second timestampable localization signal may overlap with the second payload, but not the first payload, of the first timestampable localization signal. In some embodiments, the self-localizing apparatus may be configured to receive the first payload of the first timestampable localization signal and the entire second timestampable localization signal.

[0417] In some embodiments, the first anchor may be configured to transmit the first timestampable localization signal using a transmission center frequency and a transmission frequency bandwidth. In some embodiments, the second anchor may be configured to transmit the second timestampable localization signal using the transmission center frequency and the transmission frequency bandwidth.

[0418] In some embodiments, the first anchor may be configured to transmit a plurality of first timestampable localization signals. In some embodiments, the second anchor may be configured to transmit a plurality of second timestampable localization signals. In some embodiments, each of the plurality of second timestampable localization signals may partially overlap with a corresponding one of the plurality of first timestampable localization signals.

[0419] In some embodiments, the localization system may further comprise four or more anchors. In some embodiments, the four or more anchors may comprise the first anchor and the second anchor. In some embodiments, the four or more anchors may be configured to transmit timestampable localization signals according to a transmission schedule that partially overlaps the transmission of the timestampable localization signals, thereby causing the timestampable localization system to transmit more timestampable signals per time unit than if the timestampable localization signals did not overlap.

[0420] In some embodiments, the payload of each of the first and second timestampable localization signals identifies when an anchor may be configured to transmit a localization signal during a future time slot.

[0421] In some embodiments, the self-localizing apparatus may be configured to receive an identification of when an anchor may be configured to transmit a localization signal during a future time lost, and select which timestampable signal to receive in its entirety based on the received identification.

[0422] In some embodiments, method for localization is provided. In some embodiments, the method may comprise using a first anchor to transmit a first timestampable localization signal. In some embodiments, the first timestampable localization signal may comprise a preamble followed by a payload.

[0423] In some embodiments, the method may further comprise using a second anchor to transmit a second timestampable localization signal. In some embodiments, the second timestampable localization signal may comprise a preamble followed by a payload. In some embodiments, the transmission of the second timestampable localization signal may partially overlap with the transmission of the first timestampable localization signal such that the second timestampable localization signal does not overlap the preamble of the first timestampable localization signal. In some embodiments, the first timestampable localization signal and the second timestampable localization signal may be received within a common region.

[0424] In some embodiments, the first timestampable localization signal may comprise a first ultra-wideband (UWB) signal, and the second timestampable localization signal may comprise a second UWB signal.

[0425] In some embodiments, the first timestampable localization signal may further comprises a start of frame delimiter (SFD) between the preamble and the payload. In some embodiments, the second timestampable localization signal may not overlap the SFD of the first timestampable localization signal. In some embodiments, the method may further comprise using a self-localizing apparatus to receive the preamble and the SFD of the first timestampable localization signal and the entire second timestampable localization signal.

[0426] In some embodiments, the method may further comprise using the self-localizing apparatus to determine a timestamp corresponding to the reception of the preamble or the SFD of the first localization signal; and determine position information based on a known transmission time of the first timestampable localization signal and the timestamp.

[0427] In some embodiments, the payload of the first timestampable localization signal may comprise first and second payloads and wherein the second timestampable localization signal may overlap with the second payload, but not the first payload, of the first timestampable localization signal. In some embodiments, the method may further comprise using a self-localizing apparatus to receive, the first payload of the first timestampable localization signal and the entire second timestampable localization signal.

[0428] According to another aspect of the present disclosure, a method for operating a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors. In some embodiments, the method may comprise allocating a first subset of the plurality of positioning anchors to a first subnetwork. The method may also comprise operating the first subnetwork of the first subset of positioning anchors to transmit first localization signals according to a first transmission schedule. In some embodiments, the first localization signals may be used by a self-localizing apparatus to determine position information within a first geographic region;

[0429] The method may also comprise adjusting the allocation of the plurality of positioning anchors to the first subnetwork such that a second subset of the plurality of positioning anchors may be allocated to the first subnetwork. In some embodiments, at least one positioning anchor of the first subset is not included in the second subset and at least one positioning anchor of the second subset is not included in the first subset.

[0430] The method may also comprise operating the first subnetwork of the second subset of positioning anchors to transmit second localization signals according to a second transmission schedule. In some embodiments, the second localization signals may be used by the self-localizing apparatus to determine position information within a second geographic region. In some embodiments, the first geographic region and the third geographic region do not overlap.

[0431] In some embodiments, the first localization signals may comprise first ultra-wideband (UWB) signals, and the second localization signals may comprise second UWB signals.

[0432] In some embodiments, the method may also comprise allocating a third subset of the plurality of positioning anchors to a second subnetwork, and operating the second subnetwork of the third subset of positioning anchors to transmit third localization signals according to a third transmission schedule. In some embodiments, the third localization signals may be used by a self-localizing apparatus to determine position information within a third geographic region.

[0433] In some embodiments, the method may also comprise operating the first subnetwork and the second subnetwork simultaneously. In some embodiments, the third subset of the plurality of positioning anchors may not comprise any of the positioning anchors of the first subset of the plurality of positioning anchors.

[0434] In some embodiments, the method may also comprise operating the first subnetwork of the first subset of the plurality of positioning anchors and the second subnetwork simultaneously. In

some embodiments, the third subset of the plurality of positioning anchors may comprise at least one positioning anchor of the first subset of the plurality of positioning anchors. In some embodiments, the transmission of the first and third localization signals may use at least one different transmission characteristic. In some embodiments, the at least one different transmission characteristic may comprise at least one of transmission center frequency, transmission frequency bandwidth, preamble code, and preamble modulation scheme.

[0435] In some embodiments, the method may also comprise operating the first subnetwork of the first subset of the plurality of positioning anchors and the second subnetwork simultaneously. In some embodiments, at least one of the anchors of the first subnetwork may be operated using a lower transmission power to reduce the size of the first geographic region such that first geographic region and the second geographic region do not overlap.

[0436] In some embodiments, the first subnetwork and the second subnetwork may transmit first and second localization signals using the same transmission characteristics. In some embodiments, the first and second localization signals may overlap in time.

[0437] In some embodiments, the method may also comprise adjusting the allocation of the plurality of positioning anchors to the second subnetwork such that a fourth subset of the plurality of positioning anchors may be allocated to the second subnetwork. In some embodiments, at least one positioning anchor of the third subset is not included in the fourth subset and at least one positioning anchor of the fourth subset is not included in the third subset.

[0438] In some embodiments, the method may also comprise additionally adjusting the allocation of the plurality of positioning anchors to the first subnetwork to dynamically change the geographic region serviced by the first subnetwork. In some embodiments, the allocation of the plurality of positioning anchors to the first subnetwork may be adjusted based on a known motion of at least one self-localizing apparatus serviced by the first subnetwork. In some embodiments, the motion may be a flight pattern.

[0439] In some embodiments, the method may also comprise receiving a known location of the at least one self-localizing apparatus. In some embodiments, the location may be received from the memory of the self-localizing apparatus. In some embodiments, the received known location retrieved from memory is an expected location of a self-localizing apparatus. In some embodiments, the expected location is predicted based on a time elapsed since the beginning of a trajectory execution. In some embodiments, the use of the first subnetwork in the localization system may increase positioning performance within the first geographic region.

[0440] In some embodiments, a localization system is provided. The localization system may comprise a plurality of positioning anchor. In some embodiments, the localization system may be configured to allocate a first subset of the plurality of positioning anchors to a first subnetwork. The localization system may be configured to operate the first subnetwork of the first subset of positioning anchors to transmit first localization signals according to a first transmission schedule. In some embodiments, the first localization signals may be used by a self-localizing apparatus to determine position information within a first geographic region;

[0441] The localization system may also be configured to adjust the allocation of the plurality of positioning anchors to the first subnetwork such that a second subset of the plurality of positioning anchors may be allocated to the first subnetwork. In some embodiments, at least one positioning anchor of the first subset is not included in the second subset and at least one positioning anchor of the second subset is not included in the first subset.

[0442] The localization system may also be configured to operate the first subnetwork of the second subset of positioning anchors to transmit second localization signals according to a second transmission schedule. In some embodiments, the second localization signals may be used by the self-localizing apparatus to determine position information within a second geographic region.

[0443] In some embodiments, the first localization signals may comprise first ultra-wideband (UWB) signals, and the second localization signals may comprise second UWB signals.

[0444] In some embodiments, the localization system may be further configured to allocate a third subset of the plurality of positioning anchors to a second subnetwork; and operate the second subnetwork of the third subset of positioning anchors to transmit third localization signals according to a third transmission schedule. In some embodiments, the third localization signals may be used by a self-localizing apparatus to determine position information within a third geographic region.

[0445] In some embodiments, another localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors. In some embodiments, the plurality of positioning anchors may comprise at least a first positioning anchor, a second positioning anchor, and a third positioning anchor.

[0446] In some embodiments, a first subset of positioning anchors may be configured to transmit first localization signals during a first time period according to a first transmission schedule. In some embodiments, the first localization signals may be used by a self-localizing apparatus to determine position information within a first geographic region. In some embodiments, the first subset of positioning anchors may comprise the first positioning anchor and the second positioning anchor. In some embodiments, the third positioning anchor may be configured to not transmit during the first time period.

[0447] In some embodiments, a second subset of positioning anchors may be configured to transmit second localization signals during a second subsequent time period according to a second transmission schedule. In some embodiments, the second localization signals may be used by the self-localizing apparatus to determine position information within a second geographic region. In some embodiments, the second subset of positioning anchors may comprise the first positioning anchor and the third positioning anchor. In some embodiments, the second positioning anchor may be configured to not transmit during the second time period.

[0448] According to another aspect of the present disclosure, a method for operating a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors. In some embodiments, the method may comprise using the plurality of positioning anchors to transmit first timestampable localization signals according to a first transmission schedule. In some embodiments, the first timestampable localization signals may comprise a first set of transmission characteristics and wherein the first timestampable localization signals may be used by a self-localizing apparatus to determine position information within a first geographic region.

[0449] In some embodiments, the method may further comprise using the plurality of positioning anchors to transmit second timestampable localization signals according to a second transmission schedule. In some embodiments, the second timestampable localization signals may comprise a second set of transmission characteristics. In some embodiments, the second timestampable localization signals may be used by the self-localizing apparatus to determine position information within a second geographic region.

[0450] In some embodiments, the first geographic region and the second geographic region may at least partially overlap. In some embodiments, at least some of the first timestampable localization signals and the second timestampable localization signals may be transmitted such that they overlap in time. In some embodiments, at least one type of transmission characteristic may be different in the first set of transmission characteristics and the second set of transmission characteristics to reduce interference between the at least some of the first timestampable localization signals and the second timestampable localization signals that overlap.

[0451] In some embodiments, the first timestampable localization signals may comprise first ultra-wideband (UWB) signals, and the second timestampable localization signals may comprise second UWB signals.

[0452] In some embodiments, the at least one type of transmission characteristic may comprise at least one of transmission center frequency, transmission frequency bandwidth, preamble code, and

preamble modulation scheme.

[0453] In some embodiments, one of the plurality of positioning anchors may comprise first and second antennas and may be configured to transmit one of the first timestampable localization signals using the first antenna and one of the second timestampable localization signals using the second antenna.

[0454] In some embodiments, the one positioning anchor may be configured to transmit the one first timestampable localization signal and the one second timestampable localization signal such that they overlap in time.

[0455] In some embodiments, the self-localizing apparatus may comprise at least one reception setting. In some embodiments, the method may further comprise configuring the at least one reception setting of the self-localizing apparatus to select which of the first and second timestampable localization signals to receive.

[0456] In some embodiments, the method may further comprise using the self-localizing apparatus to determine whether to receive one of the first timestampable localization signals or one of the second timestampable localization signals based on information. In some embodiments, the information may comprise configuration information received as part of a previously received timestampable localization signal. In some embodiments, the information may comprise information stored on memory of the self-localizing apparatus. In some embodiments, the information may comprise one of an internal metric of the self-localizing apparatus and an internal state of the self-localizing apparatus.

[0457] In some embodiments, the method may further comprise using one of the plurality of positioning anchors to receiving at least one of the first timestampable localization signals and the second timestampable localization signals transmitted by at least one other of the plurality of positioning anchors. In some embodiments, the method may further comprise using the one positioning anchor to determine whether to receive one of the first timestampable localization signals or one of the second timestampable localization signals based on information. In some embodiments, the information may comprise configuration information received as part of a previously received timestampable localization signal. In some embodiments, the information may comprise information stored on memory of the one positioning anchor.

[0458] In some embodiments, the first set of transmission characteristics and the second set of transmission characteristics may comprise the same center frequency and transmission frequency bandwidth.

[0459] In some embodiments, a localization system is provided. In some embodiments, the localization system may comprise a plurality of positioning anchors. In some embodiments, the plurality of positioning anchors may be configured to transmit first timestampable localization signals according to a first transmission schedule. In some embodiments, the first timestampable localization signals may comprise a first set of transmission characteristics. In some embodiments, the first timestampable localization signals may be used by a self-localizing apparatus to determine position information within a first geographic region.

[0460] In some embodiments, the plurality of positioning anchors may be configured to transmit second timestampable localization signals according to a second transmission schedule. In some embodiments, the second timestampable localization signals may comprise a second set of transmission characteristics. In some embodiments, the second timestampable localization signals may be used by the self-localizing apparatus to determine position information within a second geographic region.

[0461] In some embodiments, the first geographic region and the second geographic region may at least partially overlap. In some embodiments, at least some of the first timestampable localization signals and the second timestampable localization signals may be transmitted such that they overlap in time. In some embodiments, at least one type of transmission characteristic may be different in the first set of transmission characteristics and the second set of transmission

characteristics to reduce interference between the at least some of the first timestampable localization signals and the second timestampable localization signals that overlap.

[0462] In some embodiments, the first timestampable localization signals may comprise first ultra-wideband (UWB) signals, and the second timestampable localization signals may comprise second UWB signals.

[0463] In some embodiments, the plurality of positioning anchors may further comprises a first and a second set of three radio frequency anchors. Each of the radio frequency anchors may be configured to emit a radio frequency signal. In some embodiments, each of the radio frequency anchors may comprise an anchor antenna, an anchor clock interface operable to receive an anchor clock signal, and an analog transmission electronics.

[0464] In some embodiments, each of the radio frequency anchors may comprise digital transmission electronics operationally coupled to the anchor clock interface and the analog transmission electronics and operable to emit the radio frequency signal at a scheduled transmission time with reference to the anchor clock signal.

[0465] In some embodiments, the system may further comprise a self-localizing apparatus. In some embodiments, the self-localizing apparatus may be configured to receive the radio frequency signals. In some embodiments, the self-localizing apparatus may comprise an apparatus antenna; an apparatus clock interface configured to receive an apparatus clock signal; and apparatus analog reception electronics.

[0466] In some embodiments, the system may further comprise apparatus digital reception electronics operationally coupled to the apparatus clock interface and the apparatus analog reception electronics and configured to timestamp the received radio frequency signals with reference to the apparatus clock signal. In some embodiments, the first and second sets of radio frequency anchors may operate in geographically adjacent cells with an overlapping region. In some embodiments, the self-localizing apparatus may be configured to receive the radio frequency signals from the first set of radio frequency anchors or from the second set of radio frequency anchors when positioned in the overlapping region. In some embodiments, the plurality of positioning anchors may be configured to use at least one of separation of signals in time, separation of signals in space, or separation of signals in frequency to mitigate signal interference between the first and second sets of radio frequency anchors.

[0467] In some embodiments, the at least one type of transmission characteristic may comprise at least one of transmission center frequency, transmission frequency bandwidth, preamble code, and preamble modulation scheme.

[0468] In some embodiments, one of the plurality of positioning anchors may be further configured to receive at least one of the first timestampable localization signals and the second timestampable localization signals transmitted by at least one other of the plurality of positioning anchors.

[0469] According to another aspect of the present disclosure, a self-localizing apparatus for determining a vehicle's position is provided. In some embodiments, the self-localizing apparatus may comprise a first subsystem and a second subsystem.

[0470] In some embodiments, the first subsystem may comprise a first antenna that may be operable to receive a first radio frequency signal, and a first analog reception electronics that may be configured to amplify the first radio frequency signal. The first subsystem may also comprise a first digital reception electronics that may configured to timestamp the amplified first radio frequency signal with reference to a clock signal; and a first localization unit that may be configured to compute a first estimate of the self-localizing apparatus' position in a coordinate system based on the timestamp of the amplified first radio frequency signal.

[0471] In some embodiments, the second subsystem may comprise a second antenna that may be operable to receive a second radio frequency signal, and a second analog reception electronics that may be configured to amplify the second radio frequency signal. The second subsystem may also comprise a second digital reception electronics that may configured to timestamp the amplified

second radio frequency signal with reference to a clock signal; and a second localization unit that may be configured to compute a second estimate of the self-localizing apparatus' position in a coordinate system based on the timestamp of the amplified second radio frequency signal.

[0472] In some embodiments, each of the first subsystem and the second subsystem may be configured to be selectively used to control the vehicle without relying on the other subsystem.

[0473] In some embodiments, the first subsystem and the second subsystem may be fully redundant. For example, in some embodiments, the first subsystem may further comprise a first clock. In some embodiments, the first digital reception electronics may be configured to timestamp the amplified first radio frequency signal with reference to a first clock signal generated by the first clock. In some embodiments, the second subsystem may further comprise a second clock. In some embodiments, the second digital reception electronics may be configured to timestamp the amplified second radio frequency signal with reference to a second clock signal generated by the second clock.

[0474] In some embodiments, the first subsystem may further comprise a first synchronization unit configured to compute a clock correction for the first clock. In some embodiments, the second subsystem may further comprise a second synchronization unit configured to compute a clock correction for the second clock.

[0475] In some embodiments, the first subsystem may further comprise a first sensor for sensing at least one of a position, orientation, or velocity of the self-localizing apparatus relative to an external reference frame. In some embodiments, the first localization unit may be configured to compute the first estimate of the self-localizing apparatus' position further based on a first signal generated by the first sensor. In some embodiments, the second subsystem may further comprise a second sensor for sensing at least one of a position, orientation, or velocity of the self-localizing apparatus relative to an external reference frame. In some embodiments, the second localization unit may be configured to compute the second estimate of the self-localizing apparatus' position further based on a second signal generated by the second sensor. In some embodiments, the first sensor may be a first global property sensor; and the second sensor may be a second global property sensor.

[0476] In some embodiments, the first subsystem may further comprise a first compensation unit. In some embodiments, the first localization unit may be configured to compute the first estimate of the self-localizing apparatus' position further based on data provided by the first compensation unit. In some embodiments, the second subsystem may further comprise a second compensation unit. In some embodiments, the second localization unit may be configured to compute the second estimate of the self-localizing apparatus' position further based on data provided by the second compensation unit.

[0477] In some embodiments, the first subsystem and the second subsystem may be partially redundant. For example, in some embodiments, the self-localizing apparatus may comprise a clock. The first digital reception electronics may be configured to timestamp the amplified first radio frequency signal with reference to a first clock signal generated by the clock. The second digital reception electronics may be also configured to timestamp the amplified second radio frequency signal with reference to the first clock signal generated by the clock. In some embodiments, the self-localizing apparatus may comprise a synchronization unit. In some embodiments, the synchronization unit may be configured to compute a clock correction for the clock.

[0478] In some embodiments, the self-localizing apparatus may further comprise a sensor for sensing at least one of a position, orientation, or velocity of the self-localizing apparatus relative to an external reference frame. In some embodiments, the first localization unit may be configured to compute the first estimate of the self-localizing apparatus' position further based on a first signal generated by the sensor. In some embodiments, the second localization unit may be configured to compute the second estimate of the self-localizing apparatus' position further based on the first signal generated by the sensor. In some embodiments, the sensor is a global property sensor.

[0479] In some embodiments, the self-localizing apparatus may further comprise a compensation unit. In some embodiments, the first localization unit may be configured to compute the first estimate of the self-localizing apparatus' position further based on data provided by the compensation unit. In some embodiments, the second localization unit may be configured to compute the second estimate of the self-localizing apparatus' position further based on data provided by the compensation unit.

[0480] In some embodiments, a self-localizing apparatus for use in a localization network is provided. In some embodiments, the localization network may comprise a plurality of anchors configured to transmit radio frequency signal. In some embodiments, the self-localizing apparatus may comprise an antenna that may be operable to receive radio frequency signals from the localization network. In some embodiments, the self-localizing apparatus may comprise analog reception electronics that may be configured to amplify the radio frequency signals received by the antenna.

[0481] In some embodiments, the self-localizing apparatus may comprise digital reception electronics that may be configured to timestamp the amplified radio frequency signals with reference to a first clock signal to generate a plurality of timestamps. In some embodiments, the self-localizing apparatus may comprise a localization unit. In some embodiments, the localization unit may be configured to compute an estimate of the self-localizing apparatus' position in a coordinate system based on the timestamps, and determine to receive a selected future radio frequency signal from at least two future radio frequency signals.

[0482] In some embodiments, the localization unit may be configured to configure at least one of the antenna, the analog reception electronics, and the digital reception electronics to receive the selected radio frequency signal; and compute an updated estimate of the self-localizing apparatus' position in the coordinate system based on the received selected radio frequency signal.

[0483] In some embodiments, the self-localizing apparatus may further comprise digital and analog transmission electronics that may be configured to transmit the self-localizing apparatus' position to at least one of the plurality of anchors.

[0484] In some embodiments, the received radio frequency signals may each comprises a payload. In some embodiments, the digital reception electronics may be configured to extract the payload. In some embodiments, the payload may identify at least one anchor of the plurality of anchors that may be configured to transmit a localization signal during at least one future time slot.

[0485] In some embodiments, the localization unit may be configured to determine to receive the selected future radio frequency signal based on the location of the anchor that may be configured to transmit the selected future radio frequency signal and a variance associated with the computed estimate of the self-localizing apparatus' position.

[0486] In some embodiments, the at least two future radio frequency signals may partially overlap in time. In some embodiments, the localization unit may be configured to determine to receive the entire selected future radio frequency signal and only a portion of another of the at least two future radio frequency signals. In some embodiments, the localization unit is configured to receive one of (i) a portion of the first and the entire second of the at least two future radio frequency signals, or (ii) the entire first and none of the second of the at least two future radio frequency signals. In some embodiments, the at least two future radio frequency signals may use different preamble codes. In some embodiments, the at least two future radio frequency signals may be transmitted by different localization networks.

[0487] In some embodiments, the localization unit may be further configured to compute the estimate of the self-localizing apparatus' position in the coordinate system based on known locations of the anchors configured to transmit the radio frequencies received by the antenna.

[0488] In some embodiments, a method for determining a vehicle's position using a self-localizing apparatus is provided. In some embodiments, the self-localizing apparatus may comprise a first subsystem and a second subsystem.

[0489] In some embodiments, the method may comprise using a first antenna of the first subsystem to receive a first radio frequency signal. The method may further comprise using first analog reception electronics of the first subsystem to amplify the first radio frequency signal.

[0490] The method may further comprise using first digital reception electronics of the first subsystem to timestamp the amplified first radio frequency signal with reference to a clock signal. The method may further comprise using a first localization unit of the first subsystem to compute a first estimate of the self-localizing apparatus' position in a coordinate system.

[0491] In some embodiments, the method may comprise using a second antenna of the second subsystem to receive a second radio frequency signal. The method may further comprise using second analog reception electronics of the second subsystem to amplify the second radio frequency signal.

[0492] The method may further comprise using second digital reception electronics of the second subsystem to timestamp the amplified second radio frequency signal with reference to a clock signal. The method may further comprise using a second localization unit of the second subsystem to compute a second estimate of the self-localizing apparatus' position in a coordinate system.

[0493] The method may further comprise using one of the first subsystem and the second subsystem without relying on the other subsystem to control the vehicle.

[0494] In some embodiments, a localization method for a self-localizing apparatus in a localization network is provided. In some embodiments, the localization network may comprise a plurality of anchors configured to transmit radio frequency signals. In some embodiments, the method may comprise using an antenna to receiving radio frequency signals from the localization network. The method may also comprise using analog reception electronics to amplify the radio frequency signals received by the antenna. The method may also comprise, using digital reception electronics to timestamp the amplified radio frequency signals with reference to a first clock signal to generate a plurality of timestamps.

[0495] The method may also comprise using a localization unit to compute an estimate of the self-localizing apparatus' position in a coordinate system based on the timestamps. The method may also comprise using the localization unit to determine to receive a selected future radio frequency signal from at least two future radio frequency signals. The method may also comprise using the localization unit to configure the analog reception electronics, and the digital reception electronics to receive the selected radio frequency signal. The method may further comprise using the localization unit to compute an updated estimate of the self-localizing apparatus' position in the coordinate system based on the received selected radio frequency signal.

[0496] While certain aspects of the present disclosure have been particularly shown and described with reference to exemplary embodiments thereof, it will be understood by those of ordinary skill in the art that various changes in form and details may be made therein without departing from the spirit and scope of the present disclosure as defined by the following claims. For example, specific aspects of the present disclosure that apply to timestampable signals may apply equally well to UWB signals, or vice versa. As another example, specific aspects of the present disclosure that apply to timestampable signals may apply equally to localization signals that are not timestampable.

[0497] It will also be understood that the transceivers, apparatus, and components of the present disclosure may comprises hardware components or a combination of hardware and software components. The hardware components may comprise any suitable tangible components that are structured or arranged to operate as described herein. Some of the hardware components (e.g., the scheduler, scheduling unit controller, scheduling unit, synchronization unit, scheduling unit, localization unit, compensation unit, control unit, digital reception electronics, digital transmission electronics, etc.) may comprise processing circuitry (e.g., a processor or a group of processors) to perform the operations described herein. The software components may comprise code recorded on tangible computer-readable medium. The processing circuitry may be configured by the software

components to perform the described operations.

[0498] It is therefore desired that the present embodiments be considered in all respects as illustrative and not restrictive.

FIGURE NUMERALS

[0499] **100** Localization system [0500] **110** Scheduler [0501] **120** Scheduling unit controller [0502] **130**, **130***a*, **130***b* Transceivers [0503] **140**, **140***a*, **140***b* Self-localizing apparatuses [0504] **202** Timestampable localization signal [0505] **210** Clock [0506] **212**, **212***a*, **212***b* Antennas [0507] **214**, **214***a*, **214***b* Transceiver analog transmission electronics [0508] **216**, **216***a*, **216***b* Transceiver digital transmission electronics [0509] **218** Scheduling unit [0510] **220**, **220***a*, **220***b* Transceiver analog reception electronics [0511] **222**, **222***a*, **222***b* Transceiver digital reception electronics [0512] **224** Transceiver synchronization unit [0513] **226** Sensor [0514] **228** Global property sensor [0515] **230** Transceiver memory [0516] **302** Transceiver signal [0517] **400** Structural element [0518] **402***a*, **402***b* Clock interfaces [0519] **502**, **502***a*, **502***b*, **502***c* Self-localizing apparatus antennas [0520] **504**, **504***a*, **502***b* Self-localizing apparatus analog reception electronics [0521] **506**, **506***a*, **506***b* Self-localizing apparatus digital reception electronics [0522] **508** Self-localizing apparatus clock [0523] **510** Self-localizing apparatus synchronization unit [0524] **512**, **512***a*, **512***b* Self-localizing apparatus localization units [0525] **514**, **514***a*, **514***b* Self-localizing apparatus onboard sensors [0526] **516** Compensation unit [0527] **518** Self-localizing apparatus memory [0528] **520** Global property sensor [0529] **600** Progression of time as measured in the clock of self-localizing apparatus A [0530] **602** Arrival time of first message at self-localizing apparatus A's antenna [0531] **604** Difference between time-stamp of first message by self-localizing apparatus A's digital reception electronics and arrival time of first message at self-localizing apparatus A's antenna [0532] **606** Time-stamp of first message by self-localizing apparatus A's digital reception electronics [0533] **612** Arrival time of second message at self-localizing apparatus A's antenna [0534] **614** Difference between time-stamp of second message by self-localizing apparatus A's digital reception electronics and arrival time of second message at self-localizing apparatus A's antenna [0535] **616** Time-stamp of second message by self-localizing apparatus A's digital reception electronics [0536] **700** Structural element [0537] **702** Communication path [0538] **800** Radio frequency switch [0539] **900** Reception timestamp [0540] **902** Clock correction [0541] **904** Effect compensation [0542] **906** Corrected time of arrival [0543] **910** Remote global property [0544] **912** Compare [0545] **914** Global property model [0546] **920** Extended Kalman filter process update [0547] **922** Prior [0548] **924** Extended Kalman filter measurement update [0549] **926** Posterior [0550] **930** Location [0551] **940** Control unit [0552] **1000** Mobile robot [0553] **1002** Central processing electronics [0554] **1004** Actuators [0555] **1006** Accelerometer [0556] **1008** Gyroscope [0557] **1010** Propeller [0558] **1102** Horizontal controller [0559] **1104** Command specifying vehicle acceleration in the x-direction [0560] **1106** Command specifying vehicle acceleration in the y-direction [0561] **1110** Vertical controller [0562] **1112** Command specifying vehicle acceleration in the z-direction [0563] **1120** Reduced attitude controller [0564] **1122** Command specifying vehicle pitch rate [0565] **1124** Command specifying vehicle roll rate [0566] **1130** Yaw controller [0567] **1132** Command specifying vehicle yaw rate [0568] **1142** Body rate controller [0569] **1144** Actuator commands [0570] **1146** Movement [0571] **1200** Radial coverage of transceiver signal [0572] **1210** Wireless communication between two in-range transceivers [0573] **1220** Overlapping spatial coverage by multiple transceivers within one cell [0574] **1240** Overlapping spatial coverage by multiple transceiver cells [0575] **1410** Overlapping spatial coverage by multiple transceivers within one cell [0576] **1420** Overlapping spatial coverage by multiple transceiver cells [0577] **1610** Input parameter map with performance contours [0578] **1620** Input parameter map with binary performance [0579] **1710** Dynamic positioning performance map [0580] **1810** Panel [0581] **1820***a*, **1820***b* Location maps [0582] **1830***a*, **1830***b* Coverage requirement maps [0583] **1840***a*, **1840***b* Schedules [0584] **1910***a*, **1910***b*, **1910***c*, **1910***d* Location maps [0585] **2010***a*, **2010***b*, **2010***c*, **2010***d* Location maps [0586] **2110** Localization signal preamble

[0587] **2112** Localization signal start frame delimiter (SFD) [0588] **2114** Localization signal packet header [0589] **2116** Localization signal payload [0590] **2122** Time at which localization signal transmission begins [0591] **2124** Time at which localization signal transmission ends [0592] **2200** Transmission schedule [0593] **2202***a*, **2202***b*, **2202***c*, **2202***d* Localization signals [0594] **2310** Receiver activity [0595] **2402***a*, **2402***b*, **2402***c* Localization signals [0596] **2500** Localization system [0597] **2510** Performance map [0598] **2610** Performance map [0599] **2700** Localization system [0600] **2710** Performance map [0601] **2810** Performance map [0602] **2900** Transmission schedule [0603] **3000** Transmission schedule [0604] **3100** Flow Chart [0605] **3102** Flow chart step [0606] **3104** Flow chart step [0607] **3106** Flow chart decision [0608] **3108** Flow chart step [0609] **3110** Flow chart decision [0610] **3112** Flow chart step [0611] **3114** Flow chart decision [0612] **3116** Flow chart step [0613] **3118** Flow chart step [0614] **3210** Flow chart step [0615] **3222** Flow chart step [0616] **3124** Flow chart step [0617] **3200** Indoor and outdoor environment [0618] **3210** Building [0619] **3220** Access area [0620] **3230** Flying machine [0621] **3240** Landing area [0622] **3250** Second area [0623] **3310** Localization network [0624] **3320** Localization network [0625] **3330** Bridge anchors

Claims

1. (canceled)
2. An apparatus, comprising: a first subsystem, comprising: an antenna operable to receive a radio signal; digital reception electronics configured to timestamp the radio signal; and a first localization unit configured to compute a first estimate of a position based on the timestamp of the radio signal; and a second subsystem, comprising: a sensor operable to receive a global property signal; and a second localization unit configured to compute a second estimate of the position based on the global property signal; and wherein at least one of the first estimate and the second estimate is used to control a vehicle.
3. The apparatus of claim 2, wherein: the second subsystem comprises a global navigation satellite system (GNSS); and the global property signal is a satellite signal.
4. The apparatus of claim 2, wherein the apparatus is configured to fuse the first estimate and the second estimate.
5. The apparatus of claim 2, wherein the apparatus is configured to fuse the first estimate and the second estimate using a Kalman filter.
6. The apparatus of claim 2, wherein each of the first subsystem and the second subsystem is configured to be selectively used to control the vehicle without relying on the other subsystem.
7. The apparatus of claim 2, further comprising a control unit configured to generate a control signal for an actuator based on at least one of the first estimate and the second estimate, wherein the actuator is configured to move the vehicle.
8. The apparatus of claim 2, further comprising a control unit configured to generate control signals for a plurality of actuators based on at least one of the first estimate and the second estimate, wherein the plurality of actuators are configured to move the vehicle.
9. The apparatus of claim 8, wherein the plurality of actuators comprise a plurality of motors coupled to respective propellers.
10. The apparatus of claim 2, wherein the radio signal comprises a signal that is spread over a bandwidth that exceeds the lesser of 125 MHz or 5% of the arithmetic center frequency.
11. The apparatus of claim 2, further comprising a clock, wherein: the first subsystem is configured to timestamp the radio signal in reference to the clock; and the second subsystem is configured to timestamp the global property signal in reference to the clock.
12. A method comprising: receiving, using an antenna of a first subsystem, a radio signal; timestamping, using digital reception electronics of the first subsystem, the radio signal; computing, using a first localization unit of the first subsystem, a first estimate of a position based

on the timestamp of the radio signal; receiving, using a second subsystem, a global property signal; computing, using a second localization unit of the second subsystem, a second estimate of the position based on the global property signal; and using at least one of the first estimate and the second estimate to control a vehicle.

13. The method of claim 12, wherein: the second subsystem comprises a global navigation satellite system (GNSS); and the global property signal is a satellite signal.

14. The method of claim 12, further comprising: fusing the first estimate and the second estimate.

15. The method of claim 12, further comprising: fusing the first estimate and the second estimate using a Kalman filter.

16. The method of claim 12, wherein using the at least one of the first estimate and the second estimate to control the vehicle comprises: selectively using one of the first estimate and the second estimate to control the vehicle without relying on the other.

17. The method of claim 12, further comprising: generating a control signal for an actuator based on at least one of the first estimate and the second estimate, wherein the actuator is configured to move the vehicle.

18. The method of claim 12, further comprising: generating control signals for a plurality of actuators based on at least one of the first estimate and the second estimate, wherein the plurality of actuators are configured to move the vehicle.

19. The method of claim 18, wherein the plurality of actuators comprise a plurality of motors coupled to respective propellers.

20. The method of claim 12, wherein the radio signal comprises a signal that is spread over a bandwidth that exceeds the lesser of 125 MHz or 5% of the arithmetic center frequency.

21. The method of claim 12, further comprising: timestamping, using the first subsystem, the radio signal in reference to a clock; and timestamping, using the second subsystem, the global property signal in reference to the clock.