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GNSS Shadow Matching in a Changing Urban Environment

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GNSS Shadow Matching in a Changing Urban Environment

Abstract:

This publication describes apparatuses, methods, and techniques for performing Global Navigation Satellite System (GNSS) shadow matching in a changing urban environment. To do so, a user equipment (*e.g.*, a smartphone) utilizes a comprehensive positioning algorithm. The smartphone can measure a signal strength of satellites of the GNSS. When the signal strength matches an expected shadow, the comprehensive positioning algorithm can utilize GNSS data, area network data, inertial data, and an Urban Canyon Positioning Algorithm. The Urban Canyon Positioning Algorithm uses GNSS shadow matching data to increase user location accuracy in the urban environment. When the signal strength does not match the expected shadow, the comprehensive positioning algorithm can estimate user position using GNSS data, area network data, inertial data, and other optional localization signals (*e.g.*, step counting, visual matches against a known model of a street-level visual map). Then, the comprehensive positioning algorithm can compare and quantify differences between the signal strength with the expected shadows, and quantify discrepancies between an estimated user location from various localization signals. Based on the differences between the signal strength and the expected shadows, the comprehensive positioning algorithm can determine and map changes in the urban environment. When the GNSS shadow matching determines user location with a high degree of confidence and accuracy, the comprehensive positioning algorithm can use this information to find discrepancies in other localization signals that rely on a map model (*e.g.*, terrain height data, street-level visual maps, WiFi® hot spots). Lastly, the comprehensive positioning algorithm can adjust updates from

the Urban Canyon Positioning Algorithm near unmodeled physical features (*e.g.*, buildings, bridges, tunnels) in the urban environment.

Keywords:

Global Navigation Satellite System, GNSS, Global Positioning Satellite, GPS, shadow matching, GNSS shadow, GPS shadow, urban canyon, satellite signal, line-of-sight signal, LOS, non-line-of-sight signal, NLOS, geolocation.

Background:

User equipment (UE), such as smartphones, often utilize accelerometers, gyroscopes, magnetometers, barometers, Global Navigation Satellite System (GNSS) technology (*e.g.*, Global Positioning System (GPS), Galileo, BeiDou, GLONASS, Indian Regional Navigation Satellite System (IRNSS), Quasi-Zenith Satellite System (QZSS)), proximity sensors, ambient light sensors (ALS), touchscreen sensors, radar technology, cameras, microphones, and various other sensors that are embedded in or on the smartphone, which enhance the user experience and can play a role in the functionality of many application software (applications).

Many applications installed on a UE, such as navigation applications, social media applications, business locator applications, and so forth, depend on accurate user location. To this end, UE manufacturers and operating system (OS) developers can use algorithms that leverage different technologies to increase the user location accuracy, as is illustrated in Figure 1.
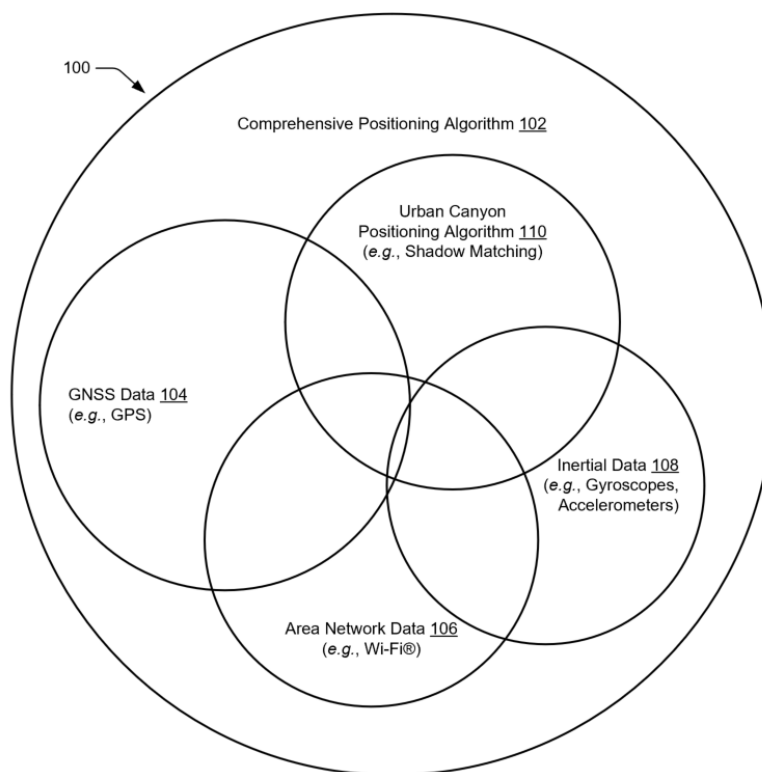
Figure 1

Figure 1 illustrates a Venn diagram 100 illustrating a comprehensive positioning algorithm 102. The comprehensive positioning algorithm 102 can utilize GNSS data 104 (*e.g.*, GPS), area network data 106 (*e.g.*, Wi-Fi® hot spots), inertial data 108 (*e.g.*, gyroscopes, accelerometers), and an Urban Canyon Positioning Algorithm 110 to determine user location, when a user is standing still, walking, running, or driving. The Urban Canyon Positioning Algorithm 110 augments the GNSS data 104 that the smartphone receives from signals sent from a "constellation" of satellites of the GNSS. Further, the Urban Canyon Positioning Algorithm 110 is useful when the user is in an urban environment.

When the user is in an urban environment, the user's smartphone can receive line-of-sight (LOS) signals and/or non-line-of-sight (NLOS) signals of satellites of the GNSS. NLOS signals have various excess path lengths and can distort the estimated user location, as is illustrated in Figure 2.
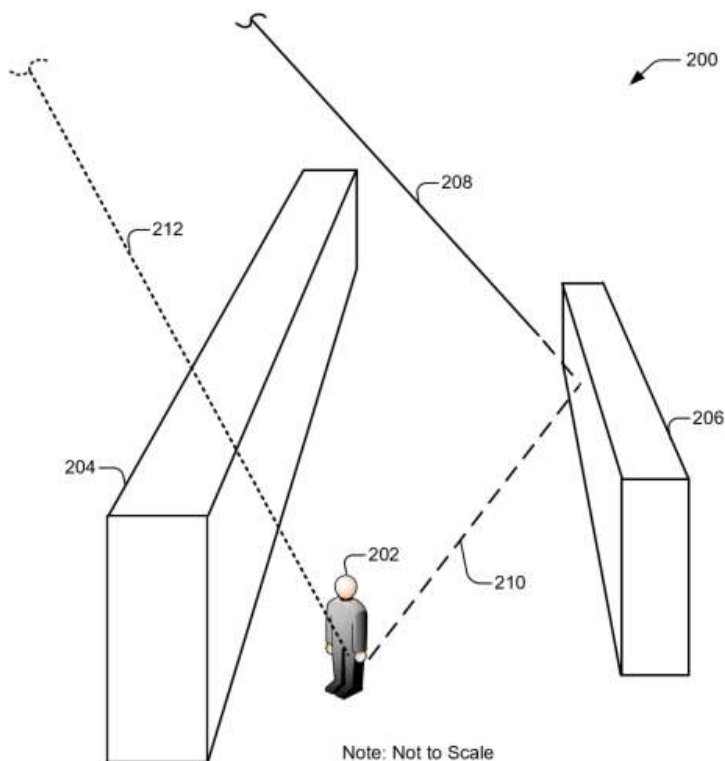
Figure 2

Figure 2 is an example urban environment 200, in which a user 202 is located between building 204 and building 206. The user 202 is carrying their smartphone, but the smartphone is not in line of sight of a satellite (the satellite is not illustrated in Figure 2) of the GNSS. Instead, the smartphone receives a reflected signal (an NLOS signal) of the satellite. In Figure 2, the solid line represents the direction of a signal 208 of the satellite of the GNSS, the dashed line represents an excess path length 210, and the dotted line represents the distance 212 of the user from the satellite of the GNSS. If the smartphone cannot differentiate an LOS signal of a satellite from an NLOS signal of the satellite, the smartphone may falsely report the user as being farther from their location by a distance equal to the illustrated excess path length 210.

The NLOS received signals reflected off physical features (*e.g.*, buildings) in a dense urban environment are often weaker than LOS signals. As such, in many cases, the smartphone can differentiate an LOS signal from an NLOS signal by measuring a carrier-to-noise density (signal

strength), *C/N0*, of a received signal. The signal strength is measured in decibels per Hertz (dB/Hz). Also, the OS developer of the Urban Canyon Positioning Algorithm 110 can map the physical features of an urban environment, such as locations and dimensions of buildings, bridges, tunnels, and so forth. The map of the urban environment may be a three-dimensional (3D) map of the urban environment. Then, the Urban Canyon Positioning Algorithm 110 can correlate the 3D map of the urban environment with the signal strength of LOS and NLOS signals to increase user location accuracy.

These techniques, however, may fail to accurately estimate the user location if the 3D map of the urban environment is not accurate. One reason for the 3D map of the urban environment not being accurate may be due to a change in the urban environment, such as demolitions and/or constructions of buildings, bridges, roadside walls, and so forth. Also, at times, the user location estimation from a vision-based localization signal (*e.g.*, a street-level visual map of the urban environment) may be inconsistent with the GNSS data 104 and/or the Urban Canyon Positioning Algorithm 110, which may indicate that the vision-based localization signal is an inaccurate and/or an outdated model of the urban environment. Therefore, it is desirable to have a technological solution that can accurately estimate the user position in a changing urban environment.

Description:

This publication describes techniques that can increase user location accuracy in a changing urban environment. In one aspect, the techniques involve performing GNSS shadow matching when a signal strength measured by a smartphone does not correlate to the 3D map of the urban environment. In another aspect, the techniques involve performing GNSS shadow

matching with other localization signals, such as a street-level visual map of the urban environment.

GNSS Shadow Matching

Physical features in the urban environment can block LOS signals from one or more satellites in the constellation of satellites of the GNSS, as is illustrated in Figure 3.
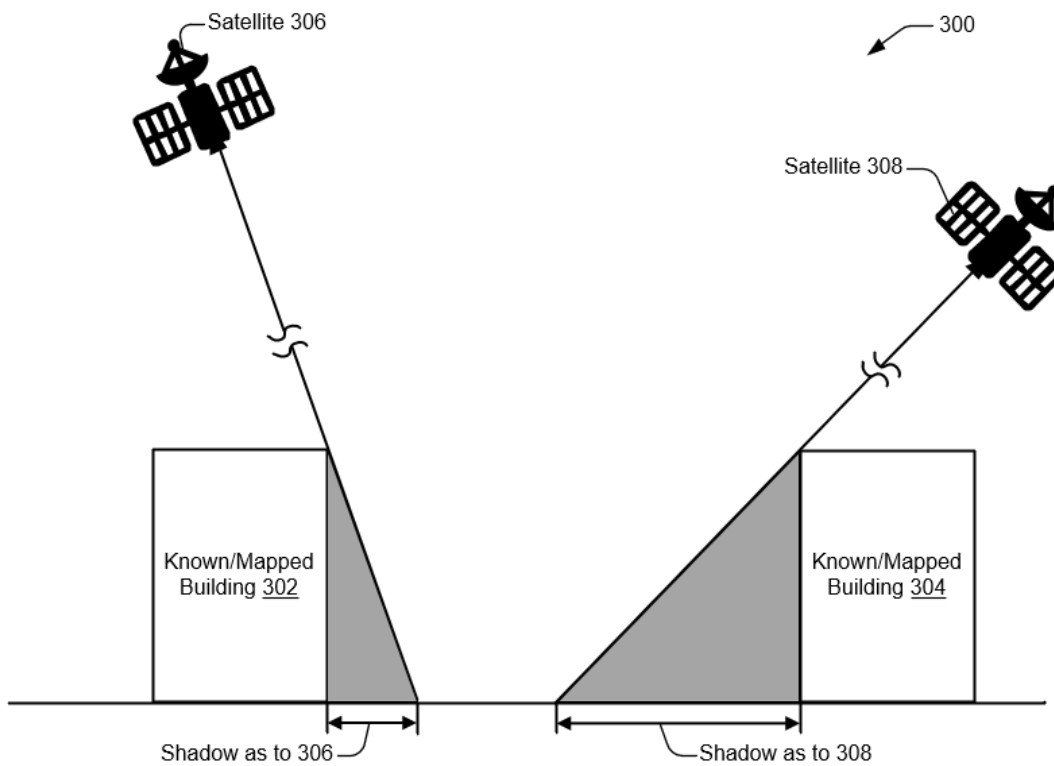

Figure 3

Figure 3 illustrates a portion of an urban environment 300, which includes building 302 and building 304. The smartphone of the user receives LOS and/or NLOS signals from satellites 306 and 308, which are part of the constellation of satellites of the GNSS. Locations that do not receive LOS signals may be considered to be shadow locations. Similar to light from a light source (*e.g.*, the Sun, a streetlight) leaving shadows when the light shines on a physical feature, physical

features can block LOS signals from one or more satellites of the GNSS, leaving invisible "shadows." Consequently, when the smartphone does not have a line of sight to one or more satellites, the smartphone is in a shadow. Figure 3 illustrates a shadow near the building 302, where the building 302 blocks LOS signals of the satellite 306 (illustrated as "shadow as to 306"). Also, Figure 3 illustrates a shadow near the building 304, where the building 304 blocks LOS signals of the satellite 308 (illustrated as "shadow as to 308"). In the shadow as to 306, the smartphone often detects a weaker signal (lower C/N_0) of the satellite 306. Similarly, in the shadow as to 308, the smartphone often detects a weaker signal of the satellite 308.

As is illustrated in Figure 3, in the shadow as to 306, the smartphone can receive NLOS signals of satellite 306. Still, in the shadow as to 306, the smartphone can receive LOS signals of the satellite 308. Similarly, in the shadow as to 308, the smartphone can receive NLOS signals of the satellite 308. Still, in the shadow as to 308, the smartphone can receive LOS signals of the satellite 306. When the user is located between the buildings 302 and 304 and between the illustrated shadows, the smartphone can receive LOS and NLOS signals of both satellites (306 and 308). Alternatively, although not illustrated as such in Figure 3, the user may only receive NLOS signals when the user is located in an urban environment, because the user may not be in a line of sight of any satellite of the GNSS (*e.g.*, the user may be under a bridge). Note that an increased number of satellites in the constellation of satellites of the GNSS can increase user location accuracy.

In one aspect, to achieve GNSS shadow matching, OS developers may create a two-dimensional (2D) building map and a 3D map of an urban environment, as is illustrated in Figure 4A.
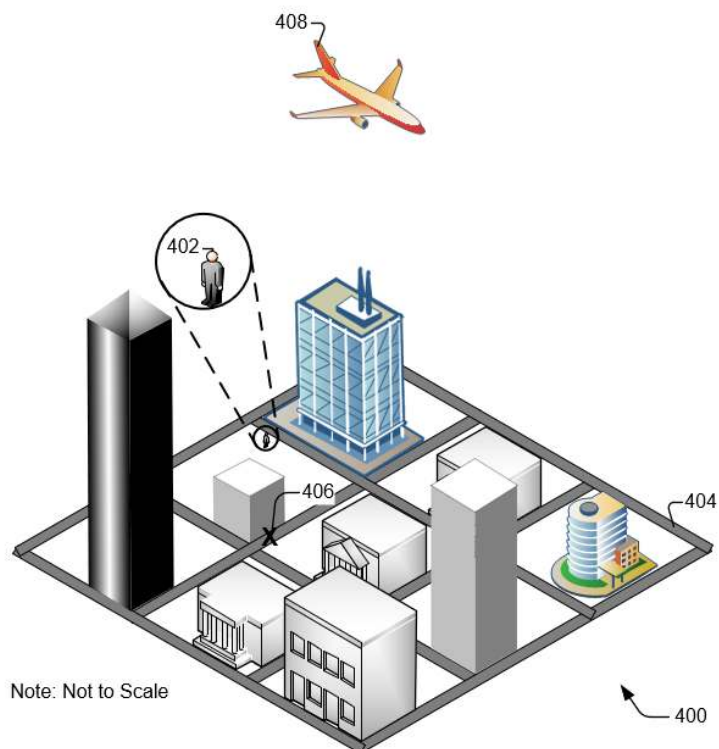
Figure 4A

Figure 4A is an example urban environment 400, illustrating a user 402 and a 2D building map 404 (illustrated as grey pathways). To establish the 2D building map 404, the OS developer may use an inertial measurement unit (IMU) to map the various locations of the urban environment 400 accurately. To establish an accurate 3D map of the example urban environment 400, the OS developer may employ an aircraft 408 equipped with a high-resolution camera to take images of the urban environment 400 from a safe altitude (*e.g.*, from approximately 5000 feet or around 1500 meters). Alternatively or additionally, the OS developer may use public records, such as building plans uploaded by a real estate developer or building permits issued by an entity (*e.g.*, a City Hall) governing the urban environment 400. Further, some cities or neighborhoods may have structure height limits for esthetic, historical, and/or safety (*e.g.*, near airports) reasons.

Then, the OS developer may utilize data from several users (employed surveyors or passive users) carrying smartphones of multiple makes and models that use navigation applications and

have the capability to measure and report the signal strength, C/N_0, of the received signals. In a sense, GNSS shadow matching refers to the reported user location, using a smartphone, matching the 2D building map 404, and the 3D map of the example urban environment 400. In a dense urban environment, however, GNSS shadow matching may be challenging to achieve, because the urban environment may change. Hence, at times, the smartphone of the user 402 can report an inaccurate location 406 that may be on a different street from the location of the user 402, because the Urban Canyon Positioning Algorithm may use an outdated 3D map, as is illustrated in Figures 4B and 4C.
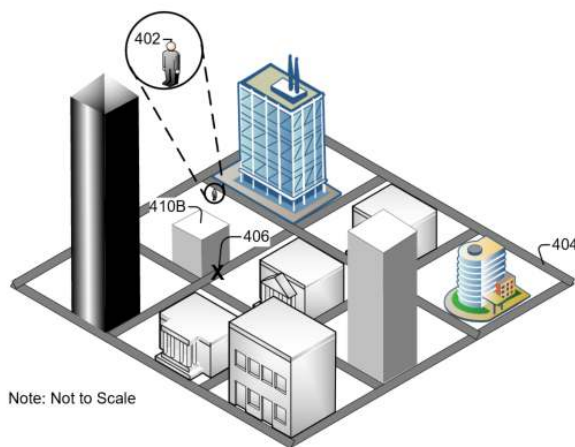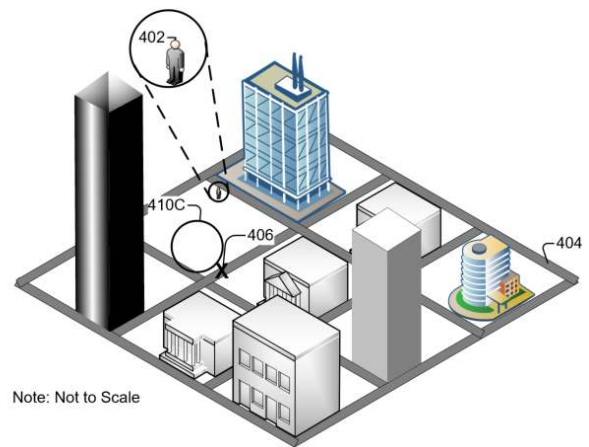

Figure 4B

Figure 4C

Assume the Urban Canyon Positioning Algorithm 110 uses an outdated 3D map that includes building 410B in Figure 4B. Also, assume since the last time the OS developer created the 3D map of the urban environment, the building 410B in Figure 4B has been demolished, and in place of the building 410B there is an open space 410C in Figure 4C. Consequently, the Urban Canyon Positioning Algorithm 110 reports the wrong location 406 instead of the location of the user 402. One way to increase user location inaccuracy due to a changing urban environment is to periodically map the 2D building map 404 and update the 3D map of the urban environment. This solution, among other limiting factors, is prohibitively expensive. Also, the OS developer

may elect to map the 2D building map 404 and the 3D map of a select number of urban environments (*e.g.*, cities with high populations) and use some aspects of the GNSS shadow matching in other urban environments (*e.g.*, towns with low populations).

"Reverse" GNSS Shadow Matching

Some of the techniques used to perform GNSS shadow matching between a 3D map of an urban environment and the signal strength of LOS signals received by the smartphones may be used to perform a "reverse" GNSS shadow matching, as is illustrated in Figure 5.
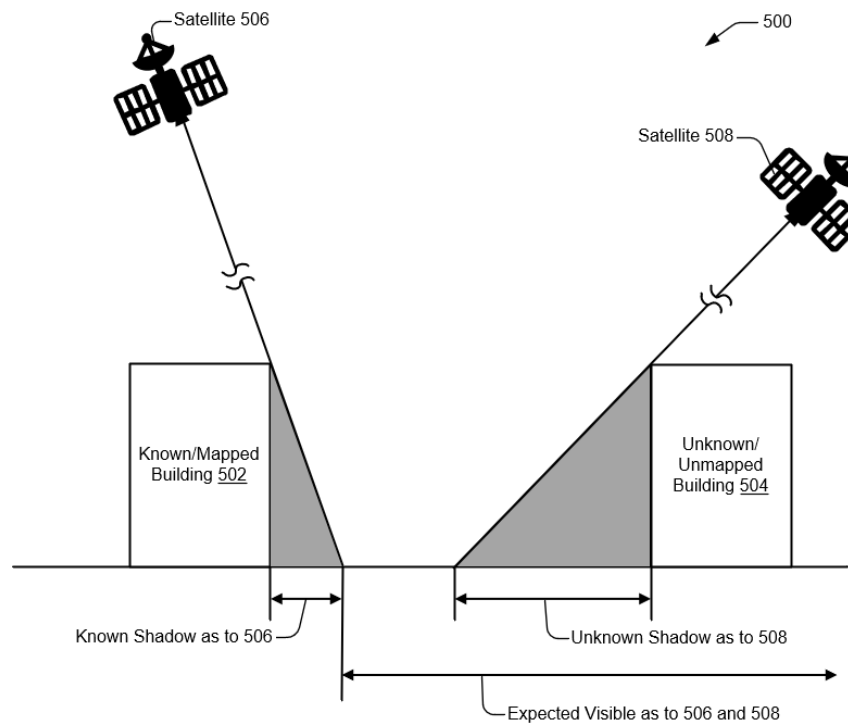

Figure 5

Figure 5 is a portion of an urban environment 500, which includes a known (mapped) building 502 and an unknown (unmapped) building 504. The smartphone of the user receives LOS and/or NLOS signals from satellites 506 and 508, which are part of the constellation of satellites

of the GNSS. As is in the case of the GNSS shadow matching illustrated in Figure 3, locations that do not receive LOS signals may be shadow locations.

Assume the user is in an area where their smartphone with the Urban Canyon Positioning Algorithm 110 expects the user to be in a line of sight to the satellites 506 and 508 (illustrated as "expected visible as to 506 and 508"). The smartphone of the user, however, detects a weak signal (low C/N_0) of the satellite 508 near the unmapped building 504 (illustrated as "unknown shadow as to 508") and a strong signal (high C/N_0) of the satellite 506. Also, similar observations are made from several users, at all times of the day, and from users using smartphones of various makes and models. Differently stated, the mismatch of the 3D map and the signal strength of the expected LOS signals are genuine and persistent. As such, it may be concluded that the 3D map of the urban environment 500 is outdated. Note that Figure 5 illustrates a new building (building 504), which may have been constructed after the OS developer of the Urban Canyon Positioning Algorithm 110 created the 3D map of the urban environment 500. Although not illustrated as such in Figure 5, in another scenario, the smartphone of the user can detect a strong signal where the Urban Canyon Positioning Algorithm 110 predicts a weak signal due to a mapped (known) building. In that scenario, it may be concluded that the 3D map is outdated and that the mapped (known) building was demolished.

A user (passive user) may be provided with controls allowing the user to make an election as to both if and when systems, programs, or features described herein may enable collection of user information (*e.g.*, information about a user's social network, social actions, social activities, profession, a user's preferences, or a user's current location), and if the user is sent content or communications from a server. In addition, certain data may be treated in one or more ways before it is stored or used, so that personally identifiable information is removed. For example, a

user's identity may be treated so that no personally identifiable information can be determined for the user. Thus, the user may have control over what information is collected about the user, how that information is used, and what information is provided to the user. The user can also disable the Urban Canyon Positioning Algorithm 110 and may choose to rely only on GNSS data, area network data, and inertial data, when utilizing applications that depend on user location (*e.g.*, navigation applications).

GNSS Shadow Matching in a Changing Urban Environment

Whenever there is a mismatch between a 3D map of an urban environment and a signal strength received by the smartphone of the user, the Urban Canyon Positioning Algorithm 110 can perform the following steps to increase user location accuracy:

1. Estimate user position using GNSS data 104, area network data 106 (*e.g.*, Wi-Fi® hot spots), and inertial data 108 (*e.g.*, gyroscopes, accelerometers);

2. Compare the signal strength of signals of the constellation of satellites of the GNSS with expected shadows in an urban environment;

3. Determine changes in the urban environment; and

4. Adjust updates from the Urban Canyon Positioning Algorithm 110 near the unmodeled physical features in the urban environment.

Estimating User Position

As is illustrated in the Venn diagram 100 in Figure 1, the smartphone using the comprehensive positioning algorithm 102 can utilize the GNSS data 104, the area network data 106, the inertial data 108, and the Urban Canyon Positioning Algorithm 110 to determine user

location. If the GNSS shadow matching is not accurate, the comprehensive positioning algorithm 102 can perform simultaneous localization and mapping (SLAM) algorithms by utilizing data from available resources, such as the GNSS data 104, the area network data 106, and the inertial data 108. The SLAM algorithms can run online (*e.g.*, on the smartphones of the users), offline (*e.g.*, on a server), or a combination thereof. The SLAM algorithms can offer a first degree of user location accuracy (*e.g.*, within two blocks of the urban environment).

Comparing the Signal Strength with Expected Shadows

After the comprehensive positioning algorithm 102 provides an estimation of the position of the user, the comprehensive positioning algorithm 102 can compare the signal strength received by the smartphones of the users, the estimated user location, and expected shadows in the vicinity of the user. Then (online and/or offline), the comprehensive positioning algorithm 102 can calculate and quantify mismatches between the 3D map of the urban environment and the signal strength. Note that to increase the accuracy of the calculated mismatch between the 3D map of the urban environment and the signal strength received by the smartphone of the user, the OS developer may utilize data from several users (employed surveyors or passive users) carrying smartphones of multiple makes and models that utilize navigation applications and have the capability to measure and report the signal strength, C/N_0, of the received signals.

Determining Changes in the Urban Environment

Based on the calculated mismatch between the 3D map of the urban environment and the signal strength received by the smartphone of the user, the OS developer may perform the reverse GNSS shadow matching illustrated in Figure 5. In aspects, the OS developer may utilize data from

multiple surveys, signals from multiple satellites of the GNSS, signals from various times of the day, and so forth. One reason to analyze the signal strength from various times of the day may be to account for local weather patterns (*e.g.*, passing clouds), traffic (*e.g.*, an oversized truck parked or passing in front of a building), and other temporary factors that cause the mismatch between the urban environment and the signal strength received by the smartphone of the user.

Adjusting Updates from the Urban Canyon Positioning Algorithm

The reverse GNSS shadow matching aids the OS developer in mapping new constructions and/or demolitions in the urban environment, without needing to periodically employ an IMU to map a new 2D building map and/or an aircraft 408 to take images of changes in the urban environment. After the OS developer has mapped new constructions and/or demolitions by utilizing the "reverse" GNSS shadow matching, the OS developer may use the new map in several ways. For example, if the OS developer has a high degree of confidence in the "reverse" GNSS shadow matching, the OS developer may choose to send a global update of the Urban Canyon Positioning Algorithm 110. As another example, when there is a mismatch between the 3D map of the urban environment and the signal strength, the comprehensive positioning algorithm 102 can set a higher weight on the GNSS data 104, the area network data 106, and the inertial data 108, and set a lower weight on GNSS shadow matching. As such, when the user approaches a particular area where the 3D map and the signal strength do not match, the comprehensive positioning algorithm 102 can primarily rely on the GNSS data 104, the area network data 106, and the inertial data 108, while secondarily relying on the Urban Canyon Positioning Algorithm 110 to determine user location. Also, similarly to traffic updates appearing in a display of the smartphone of the user, the comprehensive positioning algorithm 102 can alert the user by sending alerts to the

display screen of the smartphone with phrases, such as "Entering an outdated 3D map of an urban area," "Your location is determined by GPS data only," "You are within two blocks of the *Art Museum X*," and so forth.

Conclusion

This publication describes apparatuses, methods, and techniques for performing GNSS shadow matching in a changing urban environment. To do so, a smartphone utilizes a comprehensive positioning algorithm. The smartphone can measure a signal strength of satellites of the GNSS. When the signal strength matches an expected shadow, the comprehensive positioning algorithm can utilize GNSS data, area network data, inertial data, and an Urban Canyon Positioning Algorithm. The Urban Canyon Positioning Algorithm uses GNSS shadow matching data to increase user location accuracy in the urban environment. When the signal strength does not match the expected shadow, the comprehensive positioning algorithm can estimate user position using GNSS data, area network data, and inertial data. Then, the comprehensive positioning algorithm can compare and quantify differences between the signal strength with the expected shadows. Based on the differences between the signal strength and the expected shadows, the comprehensive positioning algorithm can determine and map changes in the urban environment. When the GNSS shadow matching determines user location with a high degree of confidence and accuracy, the comprehensive positioning algorithm can use this information to find discrepancies in other localization signals, which also rely on a map model. Lastly, the comprehensive positioning algorithm can adjust updates from the Urban Canyon Positioning Algorithm near unmodeled physical features in the urban environment.

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