

ENHANCED TRANSIT LOCATION SYSTEMS AND METHODS

CROSS REFERENCE TO RELATED APPLICATIONS

(01) The present application claims priority to U.S. Provisional Patent Application No. 62/893,724, filed August 29, 2019, entitled "ENHANCED TRANSIT LOCATION SYSTEMS AND METHODS," the disclosure thereof incorporated by reference herein in its entirety.

FIELD

(02) The present disclosure relates generally to transportation intelligence, and more specifically to systems and methods for enhanced identification of transit location.

SUMMARY

(03) Embodiments of the present disclosure provide systems and methods for tracking information relating to transportation vehicles. For example, some embodiments of the disclosure provide a system for enhanced location and data collection from vehicles traveling along a vehicle pathway. The system may include a communications mesh architecture of vehicle tagging devices and anchored transceivers affixed to segments of a vehicle pathway. For example, the vehicle may be a light rail train, a commuter train, a freight train, an automobile, an airplane, a ship, a space vehicle, a ski lift, a gondola, or other forms of transportation as known in the art. The transportation pathway may be any pathway along which the respective vehicle moves, such as a train track, a road, a canal or shipping lane, a runway, an airway, or other vehicle pathways as known in the art. By providing a communications mesh architecture, the enhanced transit location system may be fault tolerant while still providing highly accurate, real-time location data for vehicles.

(04) The system may include a mesh network of anchored transceivers and vehicle tagging devices. Both the anchored transceivers and the vehicle tagging devices may incorporate impulse-radio ultra-wideband (IR-UWB) transceivers for both distance ranging and backhaul data transmission, together with the transmission of other attributes relevant to vehicle tracking, including vehicle speed, charge or fuel levels, warning flags, etc.

(05) Vehicle tagging devices may be mounted in the front and/or the back of vehicles, or vehicle segments (e.g., train cars). The vehicle tagging devices may obtain ranging data and distance information from anchored transceivers affixed along a vehicle pathway (e.g., a train track, train tunnel, road, etc.) As the vehicle moves along the vehicle pathway, the vehicle tagging devices may transmit a data beacon (e.g., a “ping”) and anchored transceivers may respond with a corresponding anchor identification signal including a unique identifier for the respective anchor, together with a relative distance from the vehicle tagging device.

(06) The vehicle tagging device on the vehicle may receive the anchor identification signal. The vehicle tagging device may also include a processor and a non-transitory computer readable memory with computer executable instructions embedded thereon, the computer executable instructions configured to cause the processor to compute real-time multilateration. The vehicle tagging device may inject the vehicle's location (e.g., an x-y coordinate, x-y-z coordinate, track number and distance) into a backhaul. The backhaul may represent a chain of anchored transceivers proximately located to one another and extending along the vehicle pathway.

(07) In some examples, the vehicle may be a subway train, the vehicle pathway may be the train track, train track substrate, or subway tunnel, and the backhaul may

be the chain of anchored transceivers extending along the train track, train track substrate, or subway tunnel to a base station (e.g., a border anchored transceiver).

(08) Anchored transceivers may include a processor and a non-transitory computer readable memory with computer executable instructions embedded thereon, the computer executable instructions configured to cause the processor to compute relative distance to an approaching vehicle tagging device.

(09) The anchored transceiver may transmit the relative distance to of the vehicle tagging device, together with location data, through the backhaul to a bridge anchored transceiver. To enhance reliability, accuracy, and fault tolerance, anchored transceivers may be positioned in relatively close proximity to one another at regular intervals along the backhaul. In some examples, the anchored transceivers may be placed along girders along the walls of the tunnel spaced between 5 and 20 meters apart.

These and other objects, features, and characteristics of the system and/or method disclosed herein, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the invention. As used in the specification and in the claims, the singular form of "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

(10) The technology disclosed herein, in accordance with one or more various embodiments, is described in detail with reference to the following figures. The drawings are provided for purposes of illustration only and merely depict typical or example embodiments of the disclosed technology. These drawings are provided to facilitate the reader's understanding of the disclosed technology and shall not be considered limiting of the breadth, scope, or applicability thereof. It should be noted that for clarity and ease of illustration these drawings are not necessarily made to scale.

(11) Fig. 1A illustrates an example system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(12) Figs. 1B-1D illustrate example methods for enhanced location tracking consistent with embodiments disclosed herein.

(13) Figs. 1E-1F illustrate example transceiver devices that may be implemented in an enhanced location tracking system consistent with embodiments disclosed herein.

(14) Fig. 2 illustrates an example system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(15) Fig. 3 illustrates an example system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(16) Fig. 4A illustrates an example system enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(17) Figs. 4B-4E illustrate example spatial anchor-tag device layouts, consistent with embodiments disclosed herein.

(18) Fig. 5A illustrates an example graphical user interface for an app for communicating and interacting with a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(19) Fig. 5B illustrates an example graphical user interface for an app for communicating and interacting with a system for enhanced location tracking, consistent with embodiments disclosed herein.

(20) Fig. 5C illustrates an example graphical user interface for an app for communicating and interacting with a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(21) Fig. 6A illustrates an example graphical user interface for displaying data from a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(22) Fig. 6B illustrates an example graphical user interface for displaying data from a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(23) Fig. 6C illustrates an example graphical user interface for displaying data from a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(24) Fig. 6D illustrates an example graphical user interface for displaying data from a system for enhanced location and data collection from vehicles traveling along a vehicle pathway, consistent with embodiments disclosed herein.

(25) Fig. 7 illustrates an example computing system that may be used in implementing various features of embodiments of the disclosed technology.

(26) The figures are not intended to be exhaustive or to limit the invention to the precise form disclosed. It should be understood that the invention can be practiced with modification and alteration, and that the disclosed technology be limited only by the claims and the equivalents thereof.

DETAILED DESCRIPTION

(27) Embodiments of the present disclosure provide systems and methods for enhanced location and data collection from vehicles traveling along a vehicle pathway. In some embodiments of the disclosure, a system for enhanced location and data collection includes a plurality of vehicle tagging devices and a plurality of anchored transceivers configured to communicate using a mesh network technology. For example, the vehicle tagging devices and anchored transceivers may include IR-UWB localization transceivers.

(28) In some examples, the vehicle may be a train and the vehicle pathway may be a train track, train platform, or train tunnel, such as a subway tunnel system. The interaction between anchored transceivers mounted high on the girders in the tunnel and vehicle tagging devices installed on the trains may facilitate collection of the

geolocation of a given train. As a train moves through the tunnel, time-of-arrival (TOA) and/or time-of-flight (TOF) may be measured between anchored transceivers and vehicle tagging devices. The vehicle tagging devices may include processors and non-transitory computer readable memory with computer executable instructions embedded thereon, the computer executable instructions configured to cause the processor to compute real-time multilateration to effectively triangulate the vehicle tagging device's location and inject the train's track position and distance from a previous train station into the backhaul. Vehicle tagging devices may include a data store or be communicatively coupled to a data store, e.g., using a wireless network. The data store may include location data for multiple anchored transceivers in the system. The vehicle tagging devices may be configured to identify and distinguish intersecting points on the track and intersecting points behind a wall in order to identify correct vehicle tagging device geolocation.

(29) In some examples, interactions between stationary (e.g., anchor sensors mounted on stationary structures) and moving sensors (e.g., tag sensors mounted on moving vehicles) will produce sensor signals that can be processed by a distributed sensor network (e.g., comprising anchors and tags) for accurate positioning of vehicles with respect to stationary structures. The localization data generated by the distributed sensor network may be made available to a vehicle tracking system to track and display relative positions and other characteristics relating to the vehicles.

(30) Using a network of sensors as described herein may overcome problems associated with retrofitting a vehicle tracking system in an existing transportation system (e.g., existing subway or train systems). For example, in an existing subway system in which no network infrastructure exists inside tunnels, providing location

signals to a central vehicle tracking system requires a wireless network.. Existing subway trains may not have the technical means to transfer their position data in real time. Additionally, based on the cost of providing electrical power into the tunnels to power, any viable system must be able to provide its own power or use existing power systems, e.g., on a moving train. Embodiments disclosed herein solve these problems by measuring data on localization of the trains inside tunnels using tag sensors mounted on the trains, and transmitting the collected data wirelessly towards both tunnels entrances/ends where the data can enter the existing subway network infrastructure available on subway stations (e.g., using a backhaul network of anchor sensors). Transmitting data to both tunnels ends may also introduce redundancy and increase reliability.

(31) Fig. 1A illustrates an example system for enhanced location and data collection from vehicles traveling along a vehicle pathway. As illustrated, in some examples, the vehicle may be a train and the vehicle pathway may be a subway tunnel system. However, other example vehicles and vehicle pathways may employ the same system as would be understood by a person of ordinary skill in the art. As illustrated, the system may calculate distance ranging from a first vehicle tagging device, e.g., on a Southbound train on Track 3. As illustrated, anchored transceivers A9, A10, A11 and A12 may all be in communications range of the first vehicle tagging device and may transmit their relative distances (e.g. from an arbitrary origin) and/or time-of-transmission to the first vehicle tagging device. The first vehicle tagging device may calculate its geolocation with high accuracy by determining intersecting distances between anchored transceivers within range and using a triangulation algorithm.

(32) Figs 1B-1D illustrate example methods for enhance location tracking consistent with embodiments disclosed herein. For example, Fig. 1B illustrates a Time of Arrival (TOA) method in which a tagging device is located at intersection of three circles centered at three readers (base stations, BS); this method is called triangulation. Fig. 1C illustrates a Time Difference of Arrival (TDOA) method in which a tag device is located at intersection of three hyperbolas for which foci are the readers; this method is called trilateration. Fig 1D illustrates a Direction of Arrival (DOA) method in which a tag device is at intersection of three rays launched from three readers. There are many technical options available for implementing the enhanced location tracking methods illustrated in Figs. 1B-1D.

(33) In some examples, an enhanced localization system may implement an Ultra-Wideband (UWB) localization methodology. For exam, location tracking may be based on interaction between anchors and active tags. In some examples, time-domain UWB (TD-UWB) or software defined radio (SDR) UWB (SDR-UWB) may be used. TD-UWB may provide multiple spectra instantaneously while SDR-UWB may provide an equivalent spectrum using several sequential signal transmissions. In either methodology, time-of-arrival (TOA) and/or time-of-flight (TOF) may be measured between anchor and tag devices. Measurements of TOA using TD-UWB may be performed using, for example, the 802.15.4 range measurement protocol. Measurements of TOA using SDR-UWB may be performed using Multi-Carrier (MC) UWB (MC-UWB) and other algorithms. The whole operational cycle for transmitting, receiving and processing such TOA signals could be comparable for both TD-UWB and SDR-UWB options. To reduce power consumption, anchors may be mounted in stationary positions on the walls and/or ceiling of stationary structures (e.g., subway tunnels) and tag devices may be mounted on vehicles (e.g., train cars, the train side

walls, or roofs). In some examples, readers may be installed on the vehicle walls or roofs with tag devices installed on stationary structures. Geolocation data may be transferred to both ends of the stationary structures (e.g., subway tunnels) to make them available to RCC through the network gateways available in the stations. In some examples, anchor and/or tag devices may be powered by small batteries. The batteries may be made permanently chargeable from suitable energy harvesting devices. The difference between consumed power and power obtained from harvesting may be made small or close to zero to extend battery lives.

(34) In some example, an enhanced location tracking system may implement reader devices and passive or active tag devices. For example, passive tag devices may include RFID tags.

(35) In some examples, two or more transceivers may be implemented on tagging devices to communicate with a UHF RFID reader. Location estimation may implement techniques such as Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and fingerprint methods, as described herein.

(36) For TOA localization, a tagging device may be visible simultaneously to several readers. Localization capabilities of tagging devices can be further improved by implementing “trajectory” tracking algorithms, e.g., car coordinates will be derived not just from a single observation but from a set of consecutive measurements and predicted in a processor. Machine learning algorithms (e.g., Gaussian process regression with interpolation/extrapolation, etc.) may also be implemented to improve accuracy.

(37) TD-UWB chips configured to operate as readers may communicate to each other to exchange the TOA data needs to be processed for geolocation. Because no network infrastructure is available inside the subway tunnels the system must provide networking functionality in tunnels. For low-power low-rate data exchange as expected for tag geolocation data, the 915MHz band may provide a suitable option. Because TD-UWB chip based readers do not support this communication protocol an additional transceiver may be used to enable 915MHz wireless networking.

(38) SDR-UWB geolocation has many similar features to the TD-UWB geolocation described above. The main difference lies in implementation. TD-UWB generates pulsed signals of instantaneous wide spectrum. SDR-UWB can produce wide spectra through frequency-stepping by generating one-by-one several/many CW tones or a sequence of a few baseband signals. In SDR-UWB such received signal components are processed to “synthesize” equivalent time-domain UWB signals. A typical SDR can form digital baseband signals up to 50-60 MHz instantaneous bandwidth with several hundreds MHz clocks. Overall time-budget for full transmission-reception-processing cycles of UWB signals in TD-UWB and SDR-UWB can be comparable because time-domain reception is not performed in true real-time in TD-UWB but through sequential sampling. SDR-UWB waveforms can be updated at a rate of 10-20 μ s. A hundred of such produced spectral components would be sufficient to “synthesize” arbitrary UWB pulse at time budget of a few ms to enable ≥ 100 Hz refresh rate for SDR-UWB geolocation.

(39) In SDR-UWB, wider signal bandwidth requires more power supply while narrower signal bandwidth require less power supply. Certain minimal UWB signal bandwidths would be required to provide major system functionality such as (1) good

range resolution and precision, (2) multipath spread mitigation and others. Such bandwidth will be assessed first in simulations and then verified in hardware tests.

(40) In SDR-UWB, one way tag-reader communication protocol, which is power saving, can be implemented using multi-carrier (MC) UWB (MC-UWB) positioning methods. MC-UWB uses transmission of several (many) sub-carriers with equalized (zeroed) initial phases. When such a signal is received, its FFT is performed and phases of all dominated spectral components will be measured and processed to estimate TOA. Multi-access (multi-tag) coding can be provided by setting weighting particular sub-carriers components (binary weights 0/1 or a few bit weighting).

(41) In typical TD-UWB chip, at least a half of power is consumed by clocks which are permanently running while SDR-UWB could be set to operate with less power demands. Also, SDR-UWB tunable narrowband receivers could be more sensitive compared to sampler-based TD-UWB receivers. Finally, SDR-UWB based radios should have better RF power budget than TD-UWB radios.

(42) Importantly, UWB-SDR as a reprogrammable radio can be set for networking in addition to its geolocation operational functions. In particular, SDR supports 915MHz communication. A typical SDR chip has several Tx/Rx antenna terminals, implementing at least 2x2 MIMO scheme. Thus, one pair of Tx and Rx antenna terminals can be used to support geolocation and second pair of the Tx and Rx terminals can be used to operate the 915MHz networking as sketched below for a generic 2x2 Tx/Rx MIMO SDR chip.

(43) Additional ad-hoc wireless networking is required to transfer all tag positioning data to dedicated external users. This can be if all geolocation measurements can be transferred to the tunnel ends where they can enter the existing subway network

available on subway stations. For this the same 915MHz frequency or UWB mesh are options. This can be achieved by installing along tunnels set of a distributed repeaters or store-and-forward functionality.

(44) In some examples, a network mesh of UWB nodes may be connected by firmware to create a mesh and communicate the tagging device position data to the previous and next station gateways simultaneously.

(45) Some embodiments may incorporate SDR-UWB geolocation. Whereas TD-UWB generates pulsed signals of instantaneous wide spectrum, SDR-UWB may produce wide spectra through frequency-stepping by generating one-by-one several/many CW tones or a sequence of a few baseband signals. In SDR-UWB such received signal components may be processed to “synthesize” an equivalent time-domain UWB signals. SDR may form digital baseband signals up to 50-60 MHz instantaneous bandwidth with several hundreds MHz clocks . Overall time-budget for full transmission-reception-processing cycles of UWB signals in TD-UWB and SDR-UWB may be comparable because time-domain reception is not performed in true real-time in TD-UWB but through sequential sampling. SDR-UWB waveforms may be updated at a rate of 10-20 μ s. A hundred of such produced spectral components may be sufficient to “synthesize” arbitrary UWB pulse at time budget of a few ms to enable ≥ 100 Hz refresh rate for SDR-UWB geolocation.

(46) In SDR-UWB, wider signal bandwidth may use more power while narrower signal bandwidth may use less power. One way tagging device-anchor communication protocols may be implemented to save power is using multi-carrier (MC) UWB (MC-UWB) positioning methods. MC-UWB may use transmission of several (many) sub-carriers with equalized (zeroed) initial phases. When such a signal is received, a Fast Fourier Transform may be performed and phases of all

dominant spectral components may be measured and processed to estimate TOA. Multi-access (multi-tag) coding may be provided by setting weighting particular sub-carriers components (e.g., binary weights 0/1 or a few bit weighting).

(47) In a TD-UWB chip, at least a half of power is consumed by clocks which continuously operate while SDR-UWB may be set to operate with reduced power demands. Also, SDR-UWB may include tunable narrowband receivers that could be more sensitive compared to sampler-based TD-UWB receivers. SDR-UWB based radios may have better RF power budget than TD-UWB radios.

(48) In some examples, UWB-SDR may include a reprogrammable radio set for networking in addition to its geolocation operational functions. In particular, SDR supports 915MHz communication. An SDR chip may include several Tx/Rx antenna terminals, implementing at least a 2x2 MIMO scheme. Thus, one pair of Tx and Rx antenna terminals may be used to support geolocation and a second pair of the Tx and Rx terminals may be used to operate the 915MHz networking as sketched below for a generic 2x2 Tx/Rx MIMO SDR chip.

(49) Figs. 1E-1F illustrate example transceiver devices that may be implemented in an enhanced location tracking system. For example, Fig. 1E illustrates an example 2x2 Tx/Rx SDR layout to enable both geolocation and 915MHz operations. Both geolocation and networking operational functions may use different types of antennas connected to their respective Tx/Rx terminals. Antennae may be omnidirectional, 180-deg, high gain, circular arrays, or other antennae as known in the art.

(50) A system for enhanced location tracking may implement different example communication modes. For example, a TOA data communication exchange

between all readers involved in geolocation of the same tagging device may be implemented to combine individual TOA measurement for tag geolocation. In some examples, communication between readers and in-tunnel network nodes to gather the computed tag geolocation data may be implemented. In some examples, communication inside an in-tunnel network may be used to transfer the computed geolocation data to both tunnel ends/entrances to make them available through the in-station subway network gateways.

(51) In some examples, 915MHz frequency low-power wireless networks may be implemented by the system. In other examples, Bluetooth, ZigBee, Wi-Fi, or cellular, may be used. Fig. 1F illustrates an example communications module consistent with embodiments disclosed herein.

(52) In some examples, a UHF/UWB hybrid radio with asymmetric wireless links may be implemented as an anchor and/or a tagging device. In the downlink (reader-tag), similar to a conventional passive backscattering RFID, a transmission protocol at UHF may be adopted to control and power-up the tagging device. In the uplink (tag-reader), the energy scavenged from the UHF CW accommodates an IR-UWB transmitter to send data for a short time duration at a high data rate.

(53) A real-time locating system (RTLS) solution may be implemented. Operating at low frequencies, e.g., within the AM broadcast band (530-1710kHz), NFER systems may exploit the near-field behavior of radio signals within $\sim$ one-third of a wavelength. If close to a small antenna, the electric and magnetic components of radio waves are ninety degrees out of phase. Far from a small transmit antenna, these components converge to be in phase. By separately detecting, measuring, and comparing the electric and magnetic phases, distance measurements may be obtained.

(54) Some example systems may implement LIDAR to provide distance to a target by illuminating that target with a pulsed laser light, and measuring the reflected pulses with a sensor. Some example systems may implement Millimeter-wave (MW) radar

(55) Fig. 2 illustrates another embodiment of the example illustrated by Fig. 1. As illustrated in Fig. 2, the system may calculate distance ranging for a second vehicle tagging device on a Northbound train on Track 1. As illustrated, anchored transceiver devices A9, A10, A11 and A12 may be in range with the second vehicle tagging device and may transmit their relative distances to the second vehicle tagging device. The second vehicle tagging device may calculate its position with high accuracy by identifying intersecting distances between anchored transceivers within its range and applying a triangulation algorithm.

(56) In some examples of the embodiment illustrated by Figs. 1A and 2, anchored transceivers in a first wall adjacent to the vehicle pathway (e.g., a West wall, as illustrated) may forward packets along a corresponding backhaul (e.g., Northbound), and anchored transceivers along a second wall adjacent to the vehicle pathway and opposite the first wall (e.g., an East wall, as illustrated) may forward packets along a corresponding backhaul (e.g., Southbound). When a vehicle tagging device has calculated its position, it may inject (e.g., transmit) its location into the backhaul by sending data to the farthest anchored transceiver it can reach (e.g., which is still in range) in the direction that the train is heading, and the nearest anchored transceiver (n +/- 1) it can reach in the opposite direction. The receiving anchored transceivers forwards the location data to the farthest anchored transceivers they can reach, respectively. This forwarding process may be repeated iteratively until the location data reaches the base stations (e.g., border anchored transceivers). The location

data may then be transmitted to a centralized enhanced transit location system (ETLS). In some examples, the ETLS may be a cloud-based computer server or network of computer servers.

(57) Consistent with the embodiment illustrated by Figs. 1A and 2, Fig. 3 illustrates a location data signal being propagated along multiple backhauls from the first vehicle tagging device and Fig. 4A illustrates a location data signal being propagated along multiple backhauls from the second vehicle tagging device. In some embodiments, a location data signal may be propagated in both directions by one or both backhauls.

(58) Figs. 4B, 4C, and 4D illustrate example spatial anchor-tag device layouts. For example, Fig. 4B illustrates an example configuration implementing readers on both tunnel side walls to locate a tag on cars' roofs. In another example illustrated by Fig. 4C, readers on opposite tunnel side walls locate one tag on cars' roofs. In another example illustrated in Fig. 4D, readers on both tunnel side walls locate two tags on cars' roofs. Fig. 4E- illustrate a multi-track configuration. In such configurations, using multiple anchors to introduce redundancy may improve accuracy.

(59) In some examples, the ETLS backhaul may include an auto-healing chained mesh. Each backhaul packet may be acknowledged by the receiving anchored transceiver (n). In the event that an anchored transceiver n fails to acknowledge a packet for any reason, the transmitting anchoring transceiver (x) may attempt to reforward the packet to an alternate receiving anchoring receiver ($n-1$). To optimize this process, backhaul anchoring transceivers may be weighted as a function of their reliability to successfully forward packets, such that the most reliable path is used for any given environment.

(60) The anchored transceivers may calculate and transmit relative distance to an approaching vehicle tagging device as well as transmit location data through the backhaul to bridge anchoring transceivers.

(61) In some examples, an anchored transceiver may include one or more UWB radios operating across multiple channels (e.g., between 3 and 12 channels). In some examples, the radios may operate in a range between 3.5GHz and 6.5GHz. Example anchored transceivers may include a high gain bi-directional antenna, a low gain hemispherical antenna, a Bluetooth low-energy 2.4Ghz radio for device provisioning, an ultra-low power microcontroller, controller buttons or switches, a battery pack, and/or a DC power input for energy harvesting device or external power supply. In some examples, energy harvesting may be accomplished using wind generated by moving trains, ambient heat, solar power, induction, or other energy harvesting means as known in the art. Anchored transceivers may be securely provisioned over BLE.

(62) In some examples, vehicle tagging devices may be mounted on an external surface of a vehicle. In the example of a subway train, vehicle tagging devices may be affixed to the front and/or rear of individual train cars. Vehicle tagging devices may obtain ranging and distance data, e.g., as provided in data signals transmitted from anchored transceivers along the vehicle pathway. The vehicle tagging device may transmit a ping. The anchored transceivers may respond to the ping with a corresponding anchor identification signal. In some examples, the anchored transceivers may also transmit a relative distance from the vehicle tagging device that transmitted the initial ping. The vehicle tagging device may calculate real-time multilateration and inject location data into the backhaul.

(63) In some embodiments, a vehicle tagging device may include one or more UWB radios operating across multiple channels (e.g., between 3 and 12 channels). In some examples, the radios may operate in a range between 3.5GHz and 6.5GHz. Example vehicle tagging devices may include a high gain bi-directional antenna, a low gain hemispherical antenna, a Bluetooth low-energy 2.4Ghz radio for device provisioning, an ultra-low power microcontroller, controller buttons or switches, a battery pack, and/or a DC power input for energy harvesting device or external power supply. Example vehicle tagging devices may also include a micro-computer (e.g., a Linux based 1GHz SBC, or other microcomputer as known in the art). Example vehicle tagging devices may also include a power input port (e.g., a micro-USB DC power input, or other power supply port as known in the art). A vehicle tagging device may be securely provisioned over BLE with a unique vehicle identification.

(64) In some embodiments, the vehicle tagging devices may include two transceivers, e.g., UWB radios. The transceivers may be positioned to transmit and receive data in opposite directions, such that a first transceiver may obtain vehicle ranging data in coordination with the anchor devices, and a second transceiver may transmit and receive location data down the backhaul. By mounting a tagging device on each side of a vehicle (e.g., a front of a train and a back of a train), a front-facing tagging device may use a front facing transceiver to obtain ranging data and use a back facing transceiver to transmit the ranging data to an onboard computer and the rear-facing tagging device. The rear-facing tagging device may use its rear facing transceiver to transmit location data down the backhaul.

(65) A bridge anchoring transceiver may serve as an Internet gateways to the UWB backhaul. Example bridge anchoring transceivers may transmit vehicle

location data to an ETLS Cloud. Bridge anchoring transceivers may be installed at access points to the vehicle pathway, such as ingress and egress points for train tunnels. The bridge anchoring transceivers may be communicatively coupled to the Internet via wired or wireless networking technology.

(66) In some embodiments, a bridge anchoring transceiver may include one or more UWB radios operating across multiple channels (e.g., between 3 and 12 channels). In some examples, the radios may operate in a range between 3.5GHz and 6.5GHz. Example vehicle tagging devices may include a high gain bi-directional antenna, a low gain hemispherical antenna, a Bluetooth low-energy 2.4Ghz radio for device provisioning, an ultra-low power microcontroller, controller buttons or switches, a battery pack, and/or a DC power input for energy harvesting device or external power supply. Example bridge anchoring transceivers may also include a micro-computer and a power input port (e.g., Power-Over-Ethernet). Example bridge anchoring transceivers may also include an energy harvesting device.

(67) In some embodiments, an ETLS Cloud may aggregate vehicle location data from bridge anchoring transceivers and provide a real-time user interface, e.g., using a graphical user interface as disclosed herein.

(68) Some embodiments of the disclosure provide a method for improving accuracy of an enhanced transit location system. A method for improving accuracy of an enhanced transit location system may include coupling a digital image sensor (e.g., a digital camera) to a Vehicle tagging device and positioning the digital image sensor longitudinally along the travel axis of the vehicle so as to capture image data in front of or behind the vehicle as it moves. Survey markers may be provided along the travel path of the vehicle (e.g., a train track or a road), within the field of view of the digital image sensor. The method may include obtaining image data from the

digital image sensor while the vehicle is in motion, identifying the vehicle position at any given time based on visual queue captured in the image data from the survey markers, and verifying the vehicle position identified from the Vehicle tagging devices and Anchored transceivers using the vehicle position identified from the image data.

(69) Some embodiments of the disclosure provide an ETLS Provisioning App. For example, to facilitate provisioning, installation, and testing of the Piper ETLS system, a mobile device application may be deployed on a smartphone (e.g., a ruggedized smartphone) and distributed to personnel responsible for installing and testing the UWB equipment in the field. The ETLS Provisioning App may be communicatively coupled to anchored transceivers using a secure wireless connection, e.g., Bluetooth or WiFi. Anchored transceivers may communicate with nearby anchored transceivers within range to communicate current location for one or more vehicle tagging devices and a proximate survey marker in order to reduce provisioning time for anchored transceivers. A list of survey markers may be stored in a database located in the ETLS Cloud and synchronized with the ETLS Provisioning App when the provisioning App is connected to the network. In addition to provisioning, the ETLS Provisioning App may include a ranging feature for testing the overall health of the UWB backhaul.

(70) Figs. 5A-5C are screenshots illustrating Anchored transceivers being provisioned based on Installation Wall, Originating Station, Anchor MAC address (scanned via QR code or manually entered) and distance from the survey marker to the south of the anchored transceiver.

(71) Figs. 6A-6D illustrate an example graphical user interface for displaying vehicle positioning information. Fig. 6A illustrates a graphical user interface showing

a graphical view of a next station on the line is highlighted along with what track the train is departing from. Fig. 6B illustrates a graphical user interface showing a graphical view of a train track with the line highlighted along with what track the train is leaving from. Fig. 6C and 6D illustrate a graphical user interface displaying animations of vehicle location on a line along with corresponding data received from Vehicle tagging devices and/or anchored transceivers. The user interface may display the track that a train is on with the station at the far edge of the page. In some examples, the station background image may fade out. In some examples, the train background image may fade-in. The user interface may provide a “heads up display (HUD)” to display and/or scroll data on a screen. Train moves from side of screen until it reaches the horizontal middle of the screen then it stays centered and the track then moves with Survey Markers updating based on train position in the tunnel.

(72) In some examples, the user interface may update data displayed in real-time or semi-real-time. For example, distance along a backhaul and/or speed data for a given vehicle may be updated regularly within the user interface.

(73) As will be appreciated, the method as described herein may be performed using a computing system having machine executable instructions stored on a tangible medium. The instructions are executable to perform each portion of the method, either autonomously, or with the assistance of input from an operator.

(74) Those skilled in the art will appreciate that the disclosed embodiments described herein are by way of example only, and that numerous variations will exist. The invention is limited only by the claims, which encompass the embodiments described herein as well as variants apparent to those skilled in the art. In addition, it

should be appreciated that structural features or method steps shown or described in any one embodiment herein can be used in other embodiments as well.

(75) As used herein, the terms logical circuit and component might describe a given unit of functionality that can be performed in accordance with one or more embodiments of the technology disclosed herein. As used herein, either a logical circuit or a component might be implemented utilizing any form of hardware, software, or a combination thereof. For example, one or more processors, controllers, ASICs, PLAs, PALs, CPLDs, FPGAs, logical components, software routines or other mechanisms might be implemented to make up a component. In implementation, the various components described herein might be implemented as discrete components or the functions and features described can be shared in part or in total among one or more components. In other words, as would be apparent to one of ordinary skill in the art after reading this description, the various features and functionality described herein may be implemented in any given application and can be implemented in one or more separate or shared components in various combinations and permutations. Even though various features or elements of functionality may be individually described or claimed as separate components, one of ordinary skill in the art will understand that these features and functionality can be shared among one or more common software and hardware elements, and such description shall not require or imply that separate hardware or software components are used to implement such features or functionality.

(76) Where components, logical circuits, or components of the technology are implemented in whole or in part using software, in one embodiment, these software elements can be implemented to operate with a computing or logical circuit capable of carrying out the functionality described with respect thereto. Various embodiments

are described in terms of this example logical circuit 1100. After reading this description, it will become apparent to a person skilled in the relevant art how to implement the technology using other logical circuits or architectures.

(77) Referring now to Fig. 7, computing system 1100 may represent, for example, computing or processing capabilities found within desktop, laptop and notebook computers; hand-held computing devices (PDA's, smart phones, cell phones, palmtops, etc.); mainframes, supercomputers, workstations or servers; or any other type of special-purpose or general-purpose computing devices as may be desirable or appropriate for a given application or environment. Logical circuit 1100 might also represent computing capabilities embedded within or otherwise available to a given device. For example, a logical circuit might be found in other electronic devices such as, for example, digital cameras, navigation systems, cellular telephones, portable computing devices, modems, routers, WAPs, terminals and other electronic devices that might include some form of processing capability.

(78) Computing system 1100 might include, for example, one or more processors, controllers, control components, or other processing devices, such as a processor 1104. Processor 1104 might be implemented using a general-purpose or special-purpose processing component such as, for example, a microprocessor, controller, or other control logic. In the illustrated example, processor 1104 is connected to a bus 1102, although any communication medium can be used to facilitate interaction with other components of logical circuit 1100 or to communicate externally.

(79) Computing system 1100 might also include one or more memory components, simply referred to herein as main memory 1108. For example, preferably random access memory (RAM) or other dynamic memory, might be used for storing information and instructions to be executed by processor 1104. Main

memory 1108 might also be used for storing temporary variables or other intermediate information during execution of instructions to be executed by processor 1104. Logical circuit 1100 might likewise include a read only memory ("ROM") or other static storage device coupled to bus 1102 for storing static information and instructions for processor 1104.

(80) The computing system 1100 might also include one or more various forms of information storage mechanism 1110, which might include, for example, a media drive 1112 and a storage unit interface 1120. The media drive 1112 might include a drive or other mechanism to support fixed or removable storage media 1114. For example, a hard disk drive, a floppy disk drive, a magnetic tape drive, an optical disk drive, a CD or DVD drive (R or RW), or other removable or fixed media drive might be provided. Accordingly, storage media 1114 might include, for example, a hard disk, a floppy disk, magnetic tape, cartridge, optical disk, a CD or DVD, or other fixed or removable medium that is read by, written to or accessed by media drive 1112. As these examples illustrate, the storage media 1114 can include a computer usable storage medium having stored therein computer software or data.

(81) In alternative embodiments, information storage mechanism 1110 might include other similar instrumentalities for allowing computer programs or other instructions or data to be loaded into logical circuit 1100. Such instrumentalities might include, for example, a fixed or removable storage unit 1122 and an interface 1120. Examples of such storage units 1122 and interfaces 1120 can include a program cartridge and cartridge interface, a removable memory (for example, a flash memory or other removable memory component) and memory slot, a PCMCIA slot and card, and other fixed or removable storage units 1122 and interfaces 1120 that

allow software and data to be transferred from the storage unit 1122 to logical circuit 1100.

(82) Logical circuit 1100 might also include a communications interface 1124. Communications interface 1124 might be used to allow software and data to be transferred between logical circuit 1100 and external devices. Examples of communications interface 1124 might include a modem or softmodem, a network interface (such as an Ethernet, network interface card, WiMedia, IEEE 802.XX or other interface), a communications port (such as for example, a USB port, IR port, RS232 port Bluetooth® interface, or other port), or other communications interface. Software and data transferred via communications interface 1124 might typically be carried on signals, which can be electronic, electromagnetic (which includes optical) or other signals capable of being exchanged by a given communications interface 1124. These signals might be provided to communications interface 1124 via a channel 1128. This channel 1128 might carry signals and might be implemented using a wired or wireless communication medium. Some examples of a channel might include a phone line, a cellular link, an RF link, an optical link, a network interface, a local or wide area network, and other wired or wireless communications channels.

(83) In this document, the terms "computer program medium" and "computer usable medium" are used to generally refer to media such as, for example, memory 1108, storage unit 1120, media 1114, and channel 1128. These and other various forms of computer program media or computer usable media may be involved in carrying one or more sequences of one or more instructions to a processing device for execution. Such instructions embodied on the medium, are generally referred to as "computer program code" or a "computer program product" (which may be

grouped in the form of computer programs or other groupings). When executed, such instructions might enable the logical circuit 1100 to perform features or functions of the disclosed technology as discussed herein.

(84) Although Fig. 7 depicts a computer network, it is understood that the disclosure is not limited to operation with a computer network, but rather, the disclosure may be practiced in any suitable electronic device. Accordingly, the computer network depicted in Fig. 7 is for illustrative purposes only and thus is not meant to limit the disclosure in any respect.

(85) Further details may be found in the attached appendices: Appendix A and Appendix B.

(86) While various embodiments of the disclosed technology have been described above, it should be understood that they have been presented by way of example only, and not of limitation. Likewise, the various diagrams may depict an example architectural or other configuration for the disclosed technology, which is done to aid in understanding the features and functionality that can be included in the disclosed technology. The disclosed technology is not restricted to the illustrated example architectures or configurations, but the desired features can be implemented using a variety of alternative architectures and configurations. Indeed, it will be apparent to one of skill in the art how alternative functional, logical or physical partitioning and configurations can be implemented to implement the desired features of the technology disclosed herein. Also, a multitude of different constituent component names other than those depicted herein can be applied to the various partitions.

(87) Additionally, with regard to flow diagrams, operational descriptions and method claims, the order in which the steps are presented herein shall not mandate

that various embodiments be implemented to perform the recited functionality in the same order unless the context dictates otherwise.

(88) Although the disclosed technology is described above in terms of various exemplary embodiments and implementations, it should be understood that the various features, aspects and functionality described in one or more of the individual embodiments are not limited in their applicability to the particular embodiment with which they are described, but instead can be applied, alone or in various combinations, to one or more of the other embodiments of the disclosed technology, whether or not such embodiments are described and whether or not such features are presented as being a part of a described embodiment. Thus, the breadth and scope of the technology disclosed herein should not be limited by any of the above-described exemplary embodiments.

(89) Terms and phrases used in this document, and variations thereof, unless otherwise expressly stated, should be construed as open ended as opposed to limiting. As examples of the foregoing: the term “including” should be read as meaning “including, without limitation” or the like; the term “example” is used to provide exemplary instances of the item in discussion, not an exhaustive or limiting list thereof; the terms “a” or “an” should be read as meaning “at least one,” “one or more” or the like; and adjectives such as “conventional,” “traditional,” “normal,” “standard,” “known” and terms of similar meaning should not be construed as limiting the item described to a given time period or to an item available as of a given time, but instead should be read to encompass conventional, traditional, normal, or standard technologies that may be available or known now or at any time in the future. Likewise, where this document refers to technologies that would be apparent

or known to one of ordinary skill in the art, such technologies encompass those apparent or known to the skilled artisan now or at any time in the future.

(90) The presence of broadening words and phrases such as “one or more,” “at least,” “but not limited to” or other like phrases in some instances shall not be read to mean that the narrower case is intended or required in instances where such broadening phrases may be absent. The use of the term “component” does not imply that the components or functionality described or claimed as part of the component are all configured in a common package. Indeed, any or all of the various components of an component, whether control logic or other components, can be combined in a single package or separately maintained and can further be distributed in multiple groupings or packages or across multiple locations.

(91) Additionally, the various embodiments set forth herein are described in terms of exemplary block diagrams, flow charts and other illustrations. As will become apparent to one of ordinary skill in the art after reading this document, the illustrated embodiments and their various alternatives can be implemented without confinement to the illustrated examples. For example, block diagrams and their accompanying description should not be construed as mandating a particular architecture or configuration.



**Ultra-wideband (UWB)
Enhanced Transit Location System (ETLS)
& Secure Communications Network
Proof of Concept 2**

Final Report

November 2018

Rev 1.06

Piper Networks

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Contractor's Note

Confidentiality

This document describes the functionality of Piper Networks, Inc.'s proprietary Equipment (as defined in the Personal Services Agreement dated November 22, 2017 by and between Metropolitan Transportation Authority and Piper Networks, Inc. (the "Agreement")). This document and its contents are proprietary to Piper Networks, Inc. and are its Confidential Information (as defined in the Agreement). This document is intended for internal review by recipient only and must be held and treated in the strictest confidence. This document may not be distributed externally or reproduced for external distribution in whole or in part in any form without express prior written permission of Piper Networks, Inc.

Abstract

Piper Networks, in partnership with Thales Group Canada, conducted a successful demonstration of integrating an Ultra-Wideband based Enhanced Train Location System (ETLS) positioning technology with Communication Based Train Control (CBTC) and Next Generation Positioning Systems (NGPS). Additionally, Piper successfully demonstrated the implementation of a new wireless Data Communications System (DCS) for managing the secure data transmission between the CBTC Zone Controller and the on-board VOBC. Piper technology exceeded all of the requirements defined by MTA and Thales in the Interface Concept and Specification Document (ICD). **The system enabled Thales to run the CBTC test train in Automatic Train Operation (ATO) with zero loss of communications averaging <2% overall packet loss and 17.5ms latency between the VOBC and the Zone Controller - significantly below the allowable thresholds of 10% packet loss and 35ms average one-way latency respectively.** In summary, Piper and Thales designed, installed, tested, and demonstrated a fully operational Ultra-Wideband powered CBTC system using an innovative unencumbered wireless data communications system on a live train along a path with interlockings in less than one year - all within budget and with minimal inconvenience to riders.

Project Requirements

- Install a real-time train positioning system based on ultra-wideband technology to provide the Thales on-board VOBC with precise calculated location data along Track B4 on the F Line between the Church Avenue to 7th Avenue stations.
- Facilitate secure, reliable data communications between the Thales on-board VOBCs and wayside Zone Controllers in the CBTC room at Church Avenue capable of maintaining connection with no loss of signal throughout the test area.
- Piper initially proposed a hybrid wireless and fiber loop solution for the data communications system but was directed by MTA to deliver a 100% wireless data communications system that required no fiber or data loop installation in the tunnels of the test area.
- Deliver ≥ 120 kbps UDP throughput from the Piper communications equipment at each end of the train where they are connected to the Thales VOBC.
- Deliver an aggregate throughput ≥ 2.4 Mbps - sufficient to maintain data communications for up to 10 trains per wireless segment.
- Run the system reliably with $< 10\%$ packet loss.
- Achieve < 35 ms average one-way packet latency from Piper on-board Tag Controller to Thales Zone Controller.
- Provide Thales with calculated position of the train along the path as an integrated data feed from the Piper Tag Controller to the Thales VOBC and NGPS on-board computers.

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- Enable Thales to test the reliability of UWB-based positioning technology as a definitive measure of train location compared with traditional CBTC and new NGPS location data.
- Collect all positioning and communications data during the testing and provide a comprehensive report to MTA at the conclusion of the project.

System Components

Piper Anchor



Purpose

The Piper Anchors provide the following:

- UWB ranging to a Piper Tag
- UWB on/off-ramp for Piper 5GHz Data Communications Network
- Piper 5GHz Data Communications Network

The Piper Anchors provide UWB ranging responses to Piper Tags when queried.

Piper Anchors also configure their two 5GHz radios to form the Piper Communication Network.

The Piper Anchor receives IP data from a Piper Tag and forwards those data to the Piper Border Router.

Also, the Piper Anchor receives IP data from a Piper Border Router and forwards to the Piper Tag.

Hardware

The Piper Anchor consists of the following electrical and mechanical components:

- Main System Board consisting of:
 - Quad-core CPU, 4x ARM Cortex A7 SoC
 - Two 2x2 MIMO 5 GHz transceivers for data communication
 - One 2x2 MIMO 2.4 GHz transceiver for provisioning and maintenance
 - Two Gigabit Ethernet controllers
- Four Directional 5 GHz antennas for data communication
- Two omnidirectional 2.4 GHz antennas for maintenance radio
- UWB Daughter board with 1 UWB radio operating across 6 channels between 3.5GHz and 6.5GHz for precision ranging and data communication
- 1 High Gain bi-directional UWB antenna
- 2 externally accessible buttons (provisioning / power reset)
- Mains 120 Volt AC to 12 Volt 2.5 Amp switching power supply
- Impermeable plastic housing with heat sink for thermal management
- Chemical Resistant Amphenol MiniBOSS M22 Power Cable Assembly

Piper Border Router



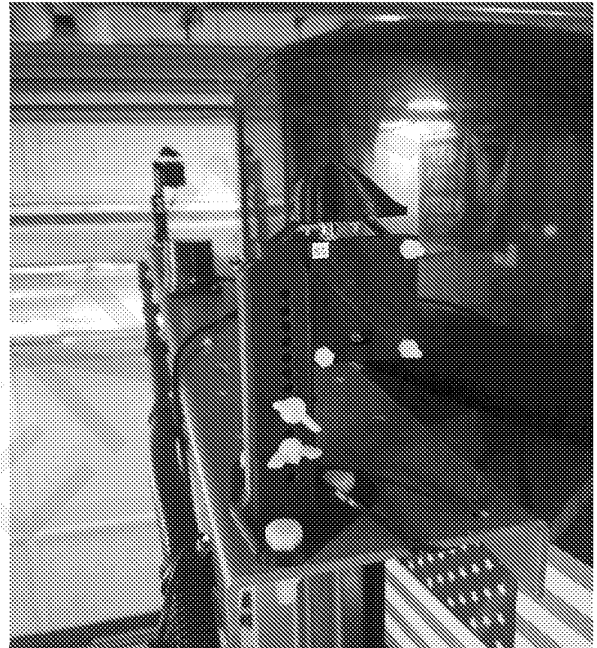
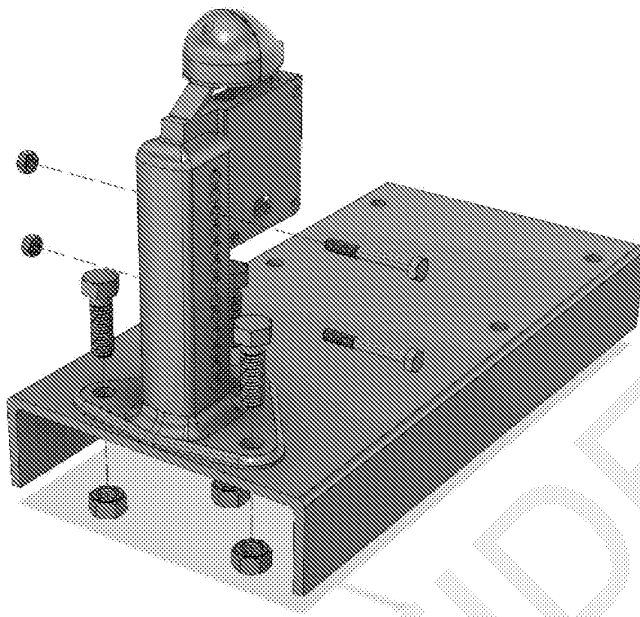
Purpose

The Piper Border Router serves as a **gateway to the 5GHz Piper Data Communications Network**. It is responsible for sending data between the MTA network and the Piper DCN. Border Routers are installed at the ingress and egress points of each tunnel. They are powered and connected to the internet via Ethernet (PoE). In addition, the Piper Border Routers also provide the same ranging functionality as Piper Anchors.

Hardware

The Piper Border Router is a Piper Anchor with an additional NPT threaded Ethernet jack for weather tight conduit connection.

Piper Tag



Left: Mock up of Piper Tag design. Right: Two Piper tags installed on the test train prior to height adjustment.

Purpose

The Piper Tag is mounted on the horizontal plastic bar provided by Thales on the front and back of a train. It is responsible for ranging to and collecting distance information from the Piper Anchor. It is also used to send and receive network data from the Piper Anchors along the train tunnel for injection into the Piper Data Communications Network.

The electronics and antenna for the POC2 test are mounted on an adjustable mounting device that allows positioning of the antenna to match the height of the train. The rounded teardrop enclosure at the top contains the antenna; in a production deployment, this would be the only part mounted on the outside of the train. The square section contains the UWB Tag board electronics - in production that would be mounted inside the bonnet, as close as possible to the antenna in order to minimize signal loss or interference. The tag board is connected to the Piper Tag Controller mounted inside the CBTC cabinet in the train's cab.

Hardware

The Piper Tag consists of the following electrical components:

- Single Board Computer consisting of:
 - Low power ARM based Microcontroller.
 - 1 UWB radio operating across 6 channels between 3.5GHz and 6.5GHz for precision ranging and data communication.
 - Micro USB jack for power and communication to Tag Controller.
- 1 omni-directional UWB antenna.
- Height adjustable mounting tower with triangular base to match the mounting bar provided by Thales.
- Weather resistant plastic housing for the SBC.
- Aerodynamic teardrop enclosure for UWB antenna.

Piper Tag Controller

Purpose

The Piper Tag Controller is the main on-board **processing** unit for Piper ranging data to compute trilateration, and for sending and receiving **network data** from the Piper DCS Network. The Piper Tag Controller has two separate physically and electrically identical parts (A and B) which are responsible for data communications and ranging, **respectively**. Each side is connected to a Piper Tag mounted on the end of the train.

The A-side provides the **on/off ramp** of data sent and received by the VOBC to the Piper DCS Network through its Piper Tag.

The B-side receives **raw ranging** data from its Piper Tag, processes it to compute the location of the train, and sends the **resulting** location data via UDP to a set of IP addresses on the train's LAN belonging to the NGPS.

The **Piper Tag** belonging the A-side is mounted on the port side of the train, the B-side on the starboard side. **Each of the** Piper Tags were connected to their respective sides of the Tag Controller by a 15-foot USB Type-A Male to Micro USB-male cable.

Hardware

The Piper Tag Controller hardware consists of two separate single-board computers (one for each side, A and B) in a one rack unit case. There are two Tag Controllers per consist. The Tag Controller for VOBC-1, at the North end is Tag Controller 03 and the Tag Controller for VOBC-2, at the South end is Tag Controller 02. Two other Tag Controllers were also built - Tag Controller 04 was used in NYC as a

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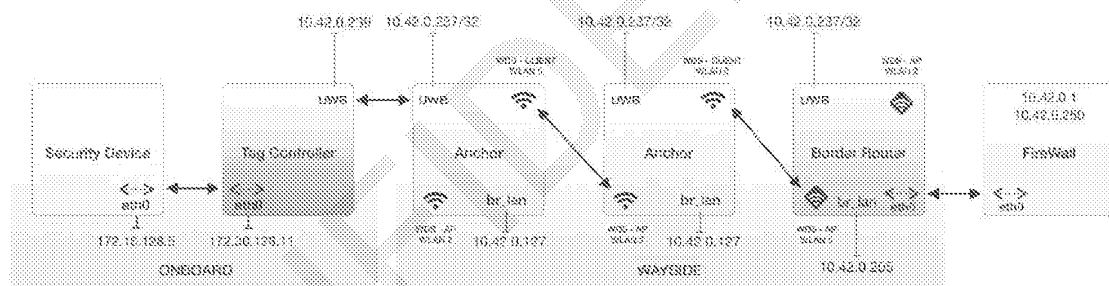
backup and to test network functionality without the need for a train, and Tag Controller 01 was used in San Diego to reproduce the deployed hardware configuration on the test network. Both devices were configured to exactly reproduce the configuration of the installed Tag Controller 03.

The Piper Tag Controllers were each supplied power by a UPS, with direct USB power output, connected to a 110VAC outlet provided by the train.

The Piper Tag Controller includes two identical sets of the following ports:

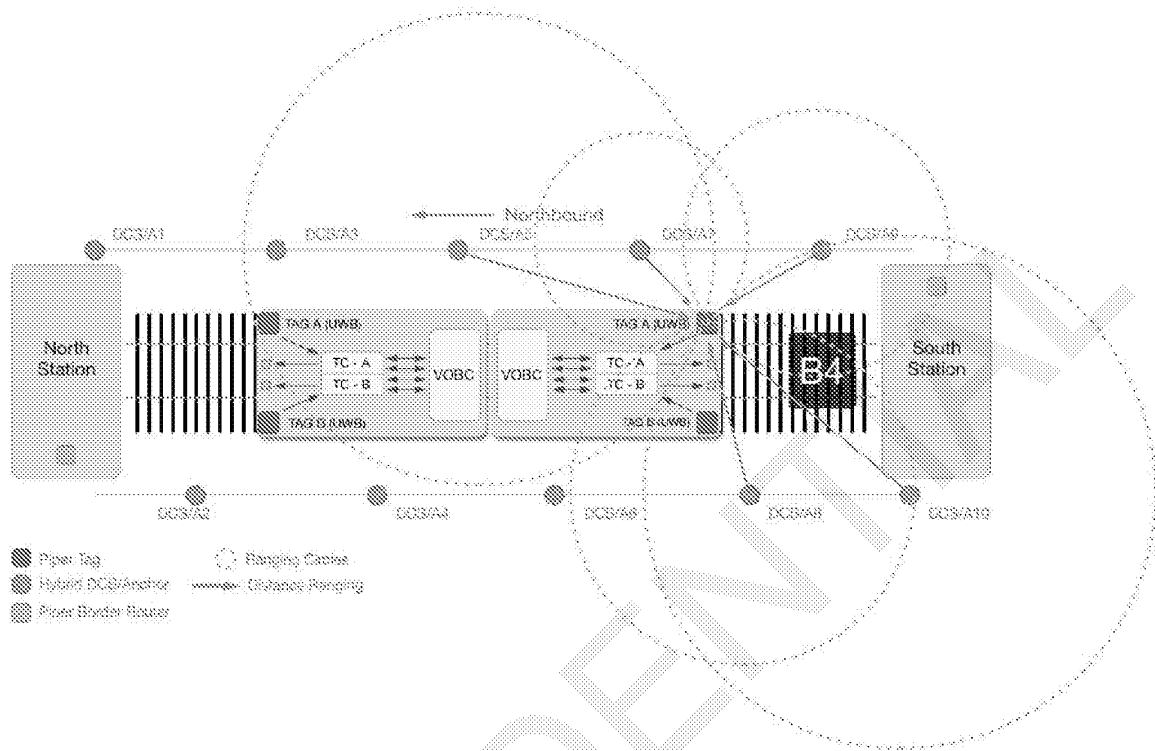
- 5V USB-A power input
- USB-A input for interface with a Piper Tag
- Two RJ-45 Ethernet ports for the transmission of ranging and positioning data
- USB-A Debug Port

Architecture



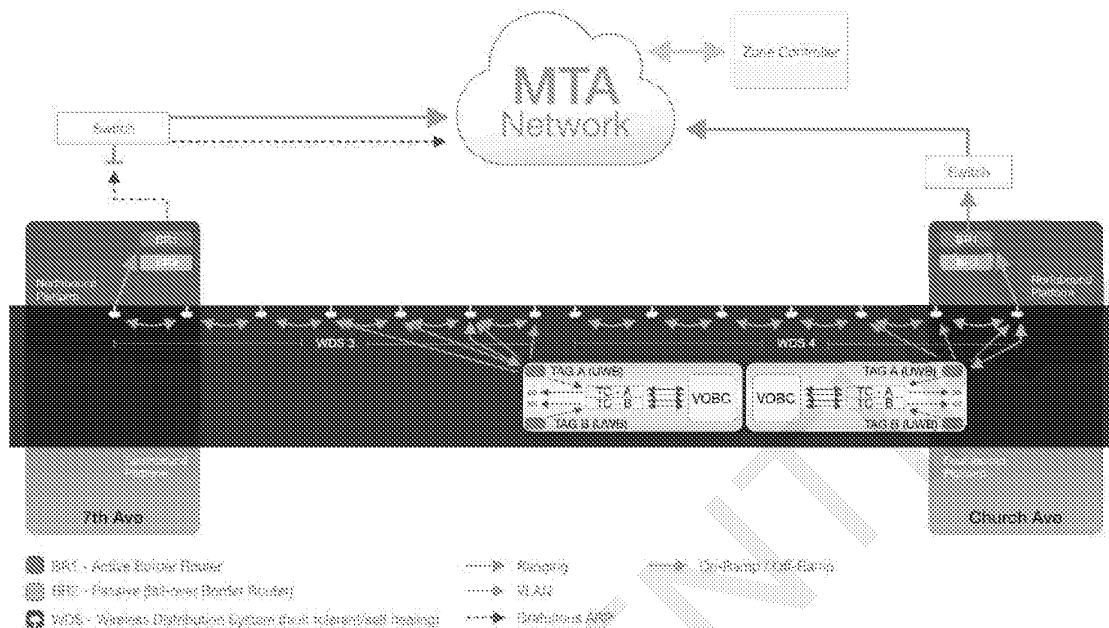
On board to wayside routing example with static IP assignment.

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Example illustration of UWB ranging between the on-board tags and anchors.

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Example illustration showing on-ramp/off-ramp of data.

Train Positioning

The interaction between Piper Anchors mounted high on the walls of the tunnel and Piper Tags installed on the train facilitates the geolocation of a given train. As a train moves through the tunnel, distance is measured between Anchors and Tags using a calculation based on the Time-of-Arrival of a radio pulse. The Tag Controllers use the ranging data, the known positions of the anchors, and a mathematical model of the track to compute the train's location. The Piper Tag Controller then produces a UDP packet defined by a Thales API and injects into the Thales trainborne network.

The Tag Controller B-side broadcasts a *Location Update* message every 500ms. The location update report (for POC2) contains:

- **tag_id** – identifies the tag to which the reported is referenced
- **edge_id** – guideway edge on which the train is located
- **offset** – arc length measured on the edge from the starting node of the edge
- **[x, y, z]** – reported location of the train in 3D local coordinates (not used in POC2)
- **estimated** – flag identifying whether the position of the train is “measured” or “estimated” (All data produced by Piper for POC2 was “measured”).

Anchor Placement

Straight track placement

Anchors were installed approximately 4" below (or as appropriate for a given section of the tunnel) the ceiling along the outer perimeter walls of the tunnel. Anchors were installed approximately 25-30 meters apart along the center/wall structures between tracks B3 and B4.

Placement in high Multipath environment

Piper Anchors are highly immune to Multipath environments (due to reliance on TOA), so placement in the tunnel and stations were not generally affected.

Anchor Radius

Piper Anchors perform distance ranging with Piper Tags installed on trains up to a 125 meter radius, given an optimal LOS environment.

Anchor Bandwidth

UWB

Anchors communicate with Piper Tags at a 6.81Mbps raw data rate, however, current hardware design limits the throughput to 1.8Mbps. Additional framing and protocol overhead reduces that to a usable bandwidth of approximately 0.5Mbps. Software and hardware design improvements are currently underway which will increase usable bandwidth to approximately 3Mbps.

Data from iperf3 testing

TCP - iperf3 (no flags)

```
[ 5] local 10.42.0.225 port 5201 connected to 10.42.0.238 port 60744
[ ID] Interval           Transfer    Bitrate
[ 5]  0.00-1.00    sec   15.9 KBytes  130 Kbits/sec
[ 5]  1.00-2.00    sec   13.5 KBytes  111 Kbits/sec
[ 5]  2.00-3.00    sec   17.5 KBytes  144 Kbits/sec
[ 5]  3.00-4.00    sec   20.3 KBytes  166 Kbits/sec
[ 5]  4.00-5.00    sec   21.7 KBytes  178 Kbits/sec
```

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```
[ 5] 5.00-6.00 sec 38.6 KBytes 317 Kbits/sec
[ 5] 6.00-7.00 sec 32.5 KBytes 265 Kbits/sec
[ 5] 7.00-8.00 sec 22.9 KBytes 188 Kbits/sec
[ 5] 8.00-9.00 sec 21.7 KBytes 178 Kbits/sec
[ 5] 9.00-10.00 sec 10.6 KBytes 86.5 Kbits/sec
[ 5] 10.00-10.03 sec 1.79 KBytes 467 Kbits/sec
```

```
-----
[ ID] Interval          Transfer      Bitrate
[ 5]  0.00-10.03 sec    217 KBytes   177 Kbits/sec
```

receiver

TCP, 220 byte packets

Command used:

```
iperf3 -l 220
```

Results:

```
[ 5] local 10.42.0.225 port 5201 connected to 10.42.0.238 port 60752
```

```
[ ID] Interval          Transfer      Bitrate
[ 5]  0.00-1.00 sec    14.2 KBytes   115 Kbits/sec
[ 5]  1.00-2.00 sec    24.9 KBytes   204 Kbits/sec
[ 5]  2.00-3.00 sec    47.0 KBytes   385 Kbits/sec
[ 5]  3.00-4.00 sec    56.2 KBytes   459 Kbits/sec
[ 5]  4.00-5.00 sec    21.5 KBytes   176 Kbits/sec
[ 5]  5.00-6.00 sec    35.7 KBytes   293 Kbits/sec
[ 5]  6.00-7.00 sec    32.5 KBytes   265 Kbits/sec
[ 5]  7.00-8.00 sec    7.17 KBytes   58.8 Kbits/sec
[ 5]  8.00-9.00 sec    17.9 KBytes   147 Kbits/sec
[ 5]  9.00-10.00 sec   20.7 KBytes   169 Kbits/sec
```

```
-----
[ ID] Interval          Transfer      Bitrate
[ 5]  0.00-10.04 sec    278 KBytes   227 Kbits/sec
```

receiver

UDP, 220 byte packets, 570 Kbps target bandwidth

Command used:

```
iperf3 -u -b 570 -l 220
```

APPENDIX "A"

Results:

```
[ 5] local 10.42.0.225 port 5201 connected to 10.42.0.238 port 47129
[ ID] Interval      Transfer    Bitrate      Jitter    Lost/Total Datagrams
[ 5]  0.00-1.00    sec  59.5 KBytes  486 Kbits/sec  5.310 ms  0/277 (0%)
[ 5]  1.00-2.00    sec  69.2 KBytes  568 Kbits/sec  5.480 ms  0/322 (0%)
[ 5]  2.00-3.00    sec  70.0 KBytes  573 Kbits/sec  5.116 ms  0/326 (0%)
[ 5]  3.00-4.00    sec  69.0 KBytes  565 Kbits/sec  5.915 ms  0/321 (0%)
[ 5]  4.00-5.01    sec  69.6 KBytes  568 Kbits/sec  5.497 ms  0/324 (0%)
[ 5]  5.01-6.00    sec  70.0 KBytes  577 Kbits/sec  5.325 ms  0/326 (0%)
[ 5]  6.00-7.00    sec  69.2 KBytes  566 Kbits/sec  4.822 ms  0/322 (0%)
[ 5]  7.00-8.00    sec  68.8 KBytes  564 Kbits/sec  7.109 ms  0/320 (0%)
[ 5]  8.00-9.00    sec  70.5 KBytes  576 Kbits/sec  5.335 ms  0/320 (0%)
[ 5]  9.00-10.00   sec  69.4 KBytes  570 Kbits/sec  5.829 ms  0/323 (0%)
[ 5] 10.00-10.00   sec   4.00 KBytes  324 Kbits/sec  9.461 ms  0/19 (0%)
-----
[ ID] Interval      Transfer    Bitrate      Jitter    Lost/Total Datagrams
[SUM] 0.0-10.1 sec  20 datagrams received out-of-order
[ 5]  0.00-10.00  sec  689 KBytes  561 Kbits/sec  9.461 ms  0/3208 (0%) receiver
```

5GHz Data Communications Network

Anchor to Anchor communication is done using a modified 802.11a WDS network. Data is transmitted from Anchor to Anchor until it reaches its destination. Each hop adds up to 1 ms of latency, and reduces useable bandwidth by 10%, so the effective bandwidth depends on the distance and number of hops to the nearest Border Router.

Data from iperf3

The following is the worst case situation, measured from the Border Router at 7th Ave. station to the anchor halfway to Church, 20 hops.

TCP - iperf3 (no flags)

```
[ 7] local 10.42.0.87 port 52616 connected to 10.42.0.77 port 5201
[ ID] Interval      Transfer    Bitrate      Retr  Cwnd
[ 7]  0.00-1.00    sec  916 KBytes  7.51 Mbits/sec   1  74.9 KBytes
[ 7]  1.00-2.00    sec  911 KBytes  7.46 Mbits/sec   0  83.4 KBytes
[ 7]  2.00-3.00    sec  895 KBytes  7.33 Mbits/sec   1  90.5 KBytes
[ 7]  3.00-4.00    sec  902 KBytes  7.39 Mbits/sec   0  97.6 KBytes
[ 7]  4.00-5.00    sec  908 KBytes  7.44 Mbits/sec   0  105 KBytes
[ 7]  5.00-6.00    sec  963 KBytes  7.89 Mbits/sec   0  115 KBytes
[ 7]  6.00-7.00    sec 1018 KBytes  8.34 Mbits/sec   0  143 KBytes
[ 7]  7.00-8.00    sec  954 KBytes  7.82 Mbits/sec   0  191 KBytes
```

APPENDIX "A"

```

[ 7] 8.00-9.00 sec 1.37 MBytes 11.5 Mbits/sec 0 255 KBytes
[ 7] 9.00-10.00 sec 1.37 MBytes 11.5 Mbits/sec 0 332 KBytes
-----
[ ID] Interval          Transfer      Bitrate      Retr
[ 7] 0.00-10.00 sec 10.0 MBytes 8.41 Mbits/sec 2          sender
[ 7] 0.00-10.00 sec 9.42 MBytes 7.86 Mbits/sec          receiver

```

UDP, 20 Mbps target bandwidth

Command used:

```
iperf3 -u -b 20M
```

Results:

```

[ 7] local 10.42.0.87 port 49056 connected to 10.42.0.77 port 5201
[ ID] Interval          Transfer      Bitrate      Total Datagrams
[ 7] 0.00-1.01 sec 2.38 MBytes 19.8 Mbits/sec 1727
[ 7] 1.01-2.00 sec 2.38 MBytes 20.1 Mbits/sec 1722
[ 7] 2.00-3.01 sec 2.39 MBytes 19.9 Mbits/sec 1731
[ 7] 3.01-4.00 sec 2.38 MBytes 20.2 Mbits/sec 1727
[ 7] 4.00-5.01 sec 2.38 MBytes 19.8 Mbits/sec 1726
[ 7] 5.01-6.01 sec 2.38 MBytes 20.0 Mbits/sec 1726
[ 7] 6.01-7.00 sec 2.38 MBytes 20.2 Mbits/sec 1725
[ 7] 7.00-8.00 sec 2.38 MBytes 20.0 Mbits/sec 1726
[ 7] 8.00-9.01 sec 2.39 MBytes 19.8 Mbits/sec 1729
[ 7] 9.01-10.00 sec 2.38 MBytes 20.1 Mbits/sec 1723
-----
[ ID] Interval          Transfer      Bitrate      Jitter      Lost/TOTAL Datagrams
[ 7] 0.00-10.00 sec 23.8 MBytes 20.0 Mbits/sec 0.000 ms 0/17262 (0%) sender
[ 7] 0.00-10.44 sec 23.8 MBytes 19.1 Mbits/sec 0.784 ms 0/17207 (0%) receiver

```

Installation Approach

Installation Environment



APPENDIX "A"

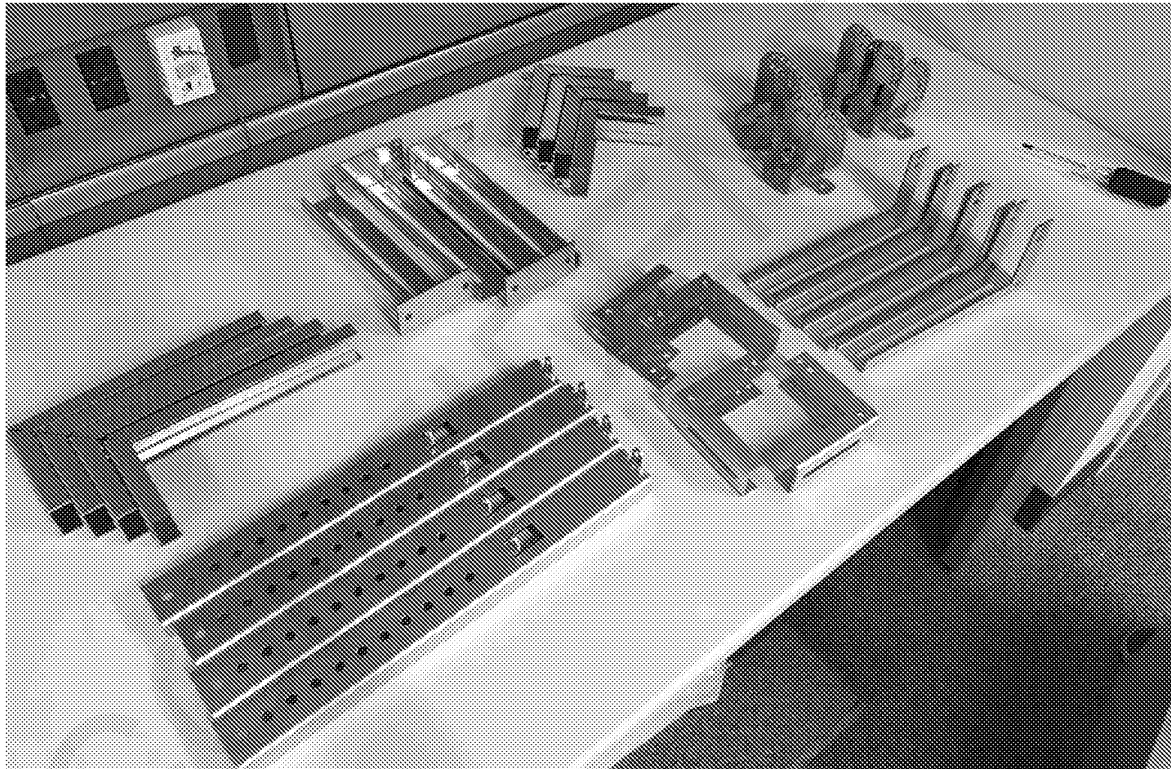


APPENDIX "A"

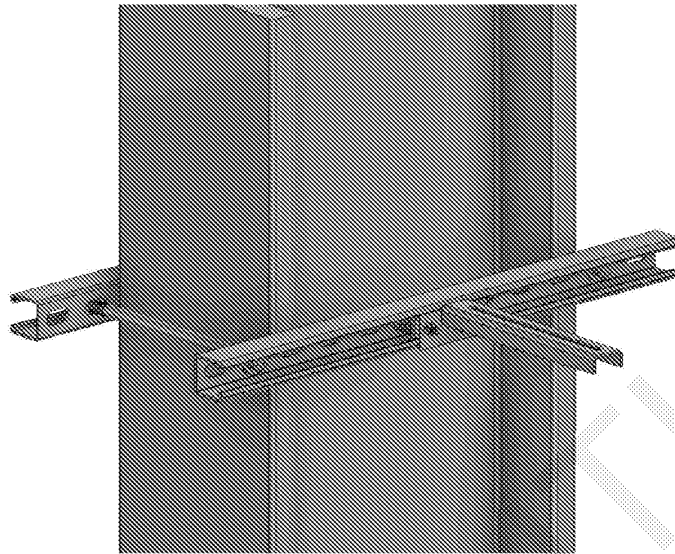
Mounting Hardware

Because of the variation of possible and accessible installation locations, we created 7 different sheet metal brackets (shown in photo below) that attach to the common mounting points on the anchor devices. The brackets were designed and custom built by Piper Networks to accommodate installation of anchors on 1) vertical concrete walls, 2) round concrete walls, 3) vertical steel beams, and 4) concrete ceiling. Several of the components can be mixed and matched between the different bracket types to accommodate unusual or unforeseen circumstances.

For more complete information about the mounting hardware, please reference document "Piper POC2 Anchor Mounting Bracket Assembly and Installation Reference, Author Duane Maxwell, 8/24/18"



APPENDIX "A"



This image shows a steel girder bracket assembly.

Outside of tunnels

All of the Piper Border Routers are installed in stations, and thus the vertical steel beam installation brackets were used most of the time. In some cases, we were able to exploit existing mounting structures. In a single case at 4th Ave., a ceiling mount was used because of the absence of other mounting opportunities. Each of the Piper Border Routers was then connected to the nearest Help Point on the platform for access to the MTA network.



APPENDIX "A"

Photo of Piper Border Router installed at 7th Ave. Station.

Photo of Piper Border Router installed in Church Ave. Station.



Onboard Equipment

Piper Tags

The Piper Tags were installed externally on the North and South ends of the consist. Each end has two tags installed, one on the starboard side and one on the port side. Nylon mounting hardware, as well as 3D-printed plastic enclosures were used to ensure safety in the unlikely event of a fall onto the track. Silicone, waterproof tape and rubber gaskets were used to for weatherproofing. Cables were routed through the side window and into the CBTC cabinet in the cab.

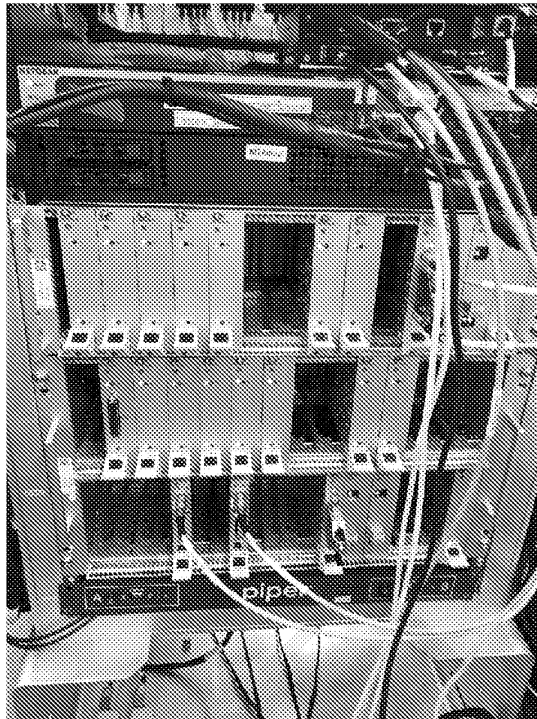
APPENDIX "A"



Piper Tag Controllers

The Piper 1U Tag Controller **was designed to fit into the Thales onboard rack as shown in this photo.** Actual installation was done inside the CBTC cabinet in the train cab. Additionally, an Uninterrupted Power Supply (UPS) **was installed to prevent downtime due to interruptions of AC power in the train cab.** The Piper Tag Controller and UPS were secured using heavy duty zip ties and foam for vibration damping to protect the **electronics.**

APPENDIX "A"



Intended placement of the Tag Controller in the VOBK rack



Actual placement of the Tag Controller due to USB cable length limitations

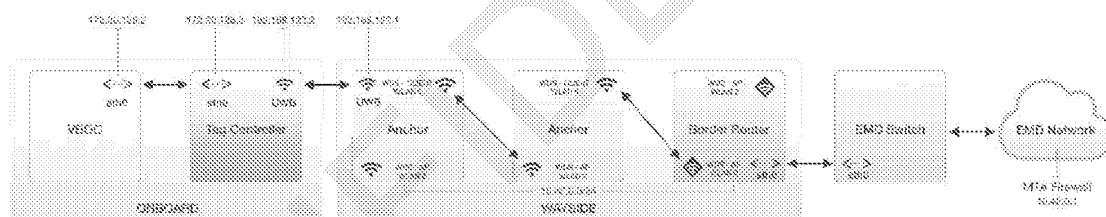
Data Communications Network

The Piper Data Communications Network consists of three main components:

- On/off-ramp
- WDS network
- Border router

The Piper Tag and Piper Anchors provide the on/off-ramp (to and from the train) using the UWB radios. The Piper Tag sends data over UWB to the Piper Anchors (on-ramp). These data are then forwarded to the Piper Data Communications Network which is a Wireless Distribution System (WDS) formed by the two 5GHz radios on the Piper Anchor. One 5GHz radio is used to send data north, the other 5GHz radio is used to send data south. This provides a full-duplex solution mitigating per hop bandwidth degradation. Any data received by a 5GHz radio is forwarded to the UWB radio and sent to the Piper Tag (off-ramp) as dictated by the routing tables.

The Piper Border Router receives data from the Piper Anchors and forwards those data to the EMD Switch. The Piper Border Router also routes data received by the EMD Switch to the Piper Data Communications Network.



Example communication path through the Piper DCN

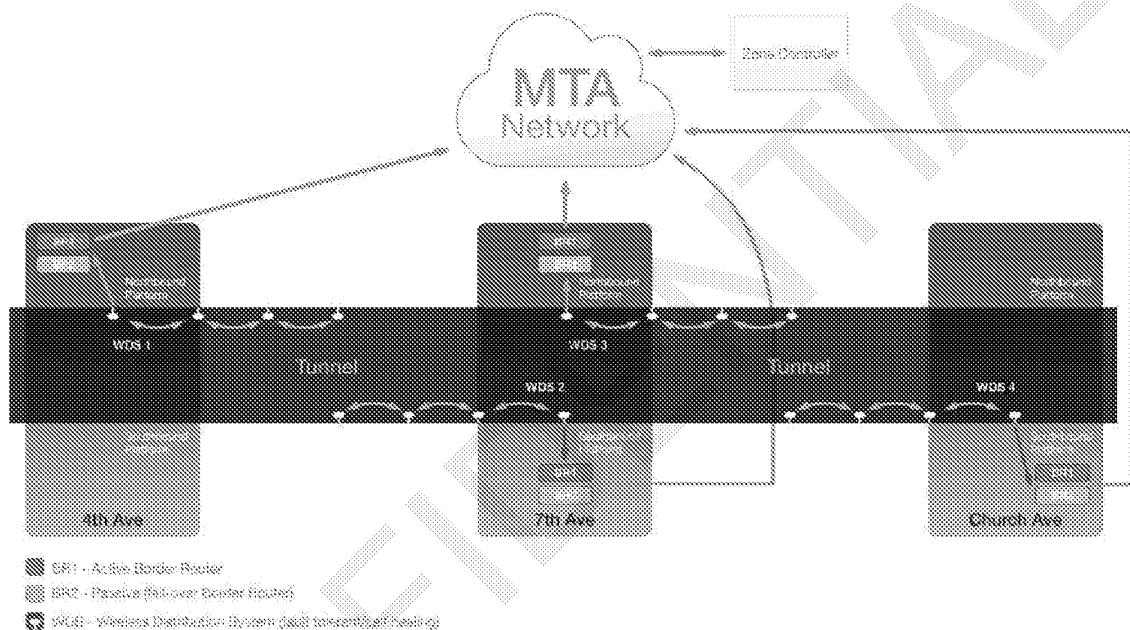
The Piper Anchors transmit beacons every 333ms. These beacons contain the tunnel location of the anchor (relative distance to the "origin") along with additional information used to form the Piper WDS. Piper Anchors use this beacon data and the RSSI from the received beacon to create routes from the anchor to the Piper Border Router. The routing algorithm minimizes latency (by hopping over adjacent anchors to a distant anchor with adequate RSSI). Due to the fact that RSSI is affected by train location, the routing algorithm must also take into consideration the location of the train, in order to route around said train by dynamically and temporarily shortening the hop distance.

Beacons are sent away from the border router, UDP heartbeats are sent toward the border router. Anchors use both the beacon and heartbeat data to determine the health of the system (and their

APPENDIX "A"

associated neighbors). If a certain number of beacons or heartbeats are lost, the anchor will effectively “heal” the network by updating routing tables to bypass any anchors that may have gone “off-line”.

As the Piper Tag moves from anchor to anchor, information is sent to the Piper Border Router which then results in a gratuitous ARP (GARP) being sent to the EMD Switch. This provides the necessary information for the EMD Switch to update its routing tables and port assignments in order to continue to route data correctly from the Zone Controller (ZC) to the Piper Tag and ultimately the VOB.

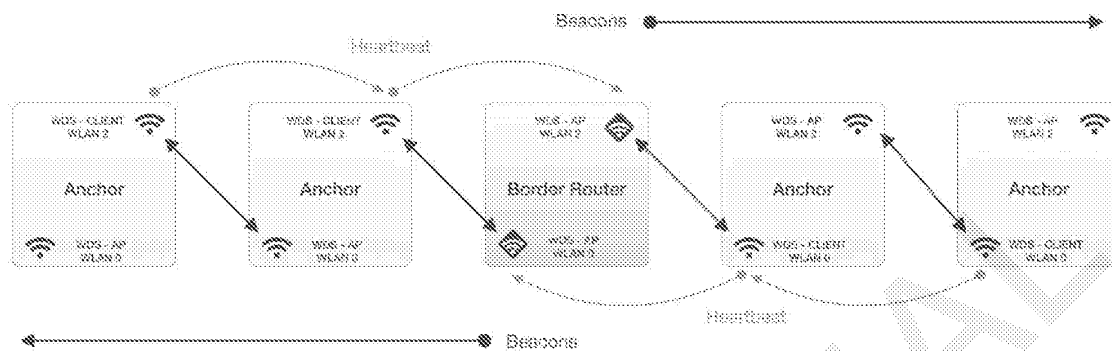


Example Piper WDS Network configuration supporting multiple tunnels

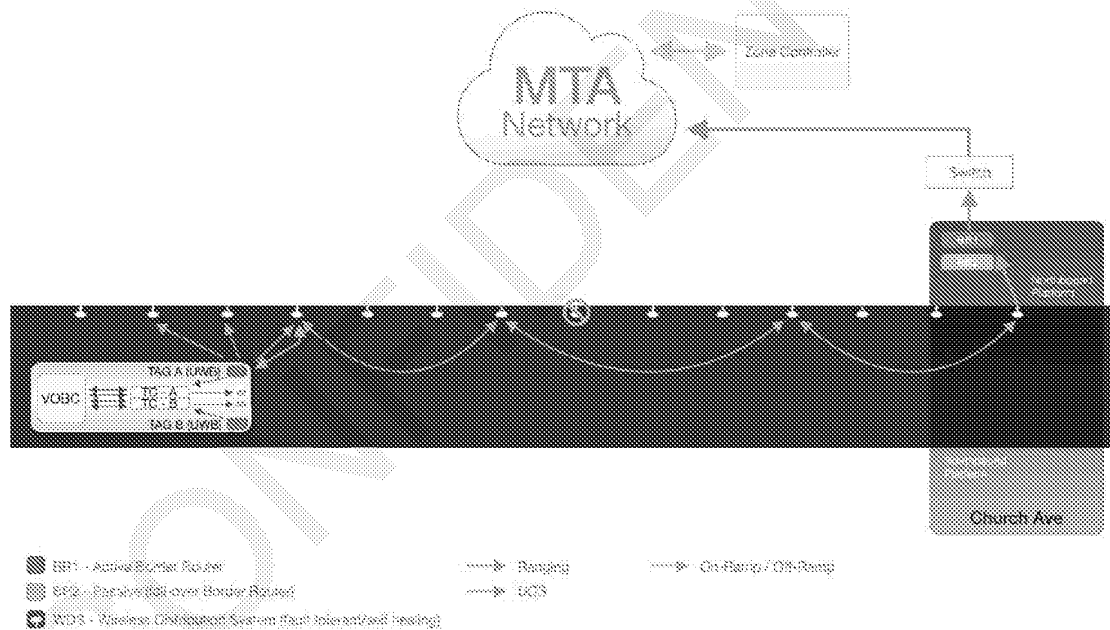
Fault Tolerance

The Piper Data Communication Network is designed such that any single Piper Anchor failure will not affect overall throughput or latency. The Piper Anchors are constantly sending and receiving beacons and heartbeat messages. The beacon data is sent from the Piper Border Routers out to the Piper Anchors that contain no children (the leaves). Likewise, leaf Piper Anchors originate heartbeat messages sent to the Piper Border Router. So, there is health data sent in both directions. The Piper Anchors and Piper Border Routers use these data (or lack thereof) to determine the health of adjacent anchors. If a certain number of heartbeats or beacons are missed, surrounding anchors will consider the failing anchor down and route around the anchor. Once the anchor is back on-line, routing to that anchor will resume.

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Piper WDS Heartbeat and Beacon paths



Example of Piper WDS routing around an offline Anchor

Firmware upgrades

The system has a mechanism to do remotely managed individual or batch firmware upgrades via the wireless Piper Data Communications Network. Each device will occasionally attempt to connect to

Piper's update server to check if an upgrade is available, and if so, download and install the upgrade. Upgrades can also be manually downloaded and installed by a network administrator.

Final Demonstration

The ETLS POC2 demonstration was presented to key leaders from the MTA on October 26, 2018. Robert Hanczor, CEO of Piper Networks and Walter Kinio, VP of Research and Innovation from Thales Group conducted the presentation - demonstrating how the UWB ETLS network would perform under several different scenarios including loss of data from the different sources that are a part of the Thales VOBC network and the Piper UWB ETLS network.

During the demonstration, Piper and Thales embarked on multiple runs on the express track between the Church Avenue station and the 7th Avenue station on the F line. On the runs, the attendees saw that the UWB ETLS network was reliable and could work in collaboration with the Thales VOBC network to provide accurate, precise and timely location data for the train.

Robert Hanczor explained that the anchors were easy to install, could be deployed in a short time-frame, and added that Piper Networks was working with Reliobotics to develop a future robotic deployment for added efficiency. He also answered several questions about the UWB ETLS network and explained that the network was strong enough to withstand a catastrophic loss of multiple anchors and still report accurate location data from the train. He also explained that the anchors could provide wireless internet to passengers in the tunnels using the 2.4GHz radios that were installed in the devices, but not used in the POC.

The photos shown below were captured during the demonstration

APPENDIX "A"



Recommendations

Intrusion Detection and Prevention

The firmware on Anchors is capable of running IDS/IPS software for detection and mitigation of known network based denial of service attacks. This system should be enabled for production deployments.

Crypto Engine and UWB Wireless Security

For POC2, the Tag (train) to Anchor (wayside) wireless communication over UWB relied on the fact that VOBC data was encrypted using an IPSec tunnel prior to being transmitted. Both the Piper Anchors and Piper Tags contain crypto processors that should be used for encrypting/decrypting UWB packets, should any unencrypted data be required to be sent to the anchors.

Secure Boot and Trusted Execution Environment

The SoC used by the Piper Anchors supports Secure Boot and ARM TrustZone. In a production rollout, Secure Boot should be enabled in order to ensure the devices would only be capable of running cryptographically signed and trusted firmware. Keys for signature verification should be stored in the TrustZone in order to mitigate boot/firmware attacks for anyone with physical access to the devices.

Border Router Redundancy

For POC2, the Border Routers serving each of the WDS networks could act as a single point of failure. Border Routers are capable of operating in an Active or Passive state, where should an Active BR fail, the Passive BR will become Active and assume control of the WDS network. This feature should be utilized in a production deployment.

2.4GHz Fast Roaming

Our hardware is capable of employing 802.11r and 802.11k for Fast Transition wireless roaming and software support is under active development. Testing in our lab has shown a consistent roaming transition latency of ~70ms. Utilization of this feature would require an additional antenna be installed on each end of the train and connected to the Tag Controllers. For production deployments requiring higher data rates for non-critical services (such as on-board WiFi), enabling this feature is recommended.

Testing with Train

Tests and data collected during GO 5600-18 on Thursday November 8th, between 10 am - 3:30 pm.

Test Data from November 8, 2018

Test Route: Church Ave. to 7th Ave., track B4

Test Start Time: 11:30 am (16:32 am (UTC))

Test End Time: 2:30 pm (19:26 pm (UTC))

Versions of FW and SW used in testing:

Tag:

Piper RTLS Firmware v3.018

Tag Controller:

Linux 4.4.34-v7+

Piper RTLS Tag Node commit 227d3db107a49eb08caa51cb1176811ca5ddbb2

Anchor:

Linux 4.9.77

Piper RTLS Tag Node Chase Build 203

Piper RTLS Firmware v3.018

Test Procedure

A test run consists of one trip, either northbound (from Church to 7th), or southbound (from 7th to Church). Data was collected from both the north Tag Controller and south Tag Controller. To monitor the performance of the network, for each run Piper recorded the output of `ping -0 -i 0.25 10.42.0.1`, which displays round-trip times for small data packets sent every quarter second. The ping data was collected from Tag Controller A. To monitor the performance of the positioning service Piper recorded the raw Tag-to-Anchor distance data generated every half second for the duration of each run. The distance data was collected from Tag Controller B. The actual distance-down-the-track number that was supplied to Thales's system was calculated from the raw data. The results of each run are provided below.

NOTE: Piper was unable to test the inherent latency of the EMD network and as a result, the latency data cannot be unequivocally attributed to the Piper network.

APPENDIX "A"

Results

Test 1

Church to 7th NB ATO 29 MPH

Start: 16:32 UTC

End: 16:43 UTC

North Tag Results

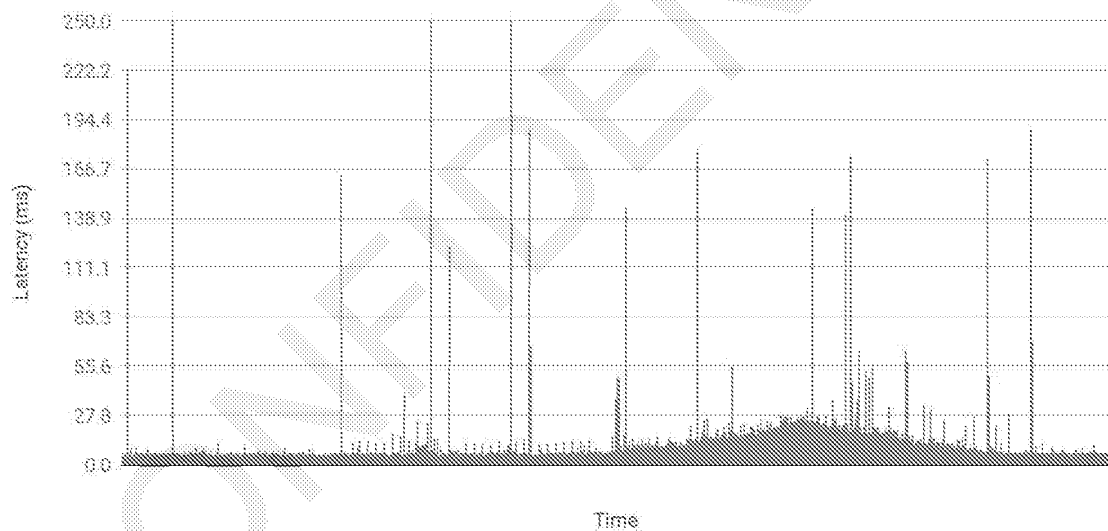
One-Way Latency: Min: 4.8ms / **Avg: 13ms** / Max: 730ms

Ping Summary:

1950 packets transmitted, 1921 received, 1% packet loss, time 489074ms

rtt min/avg/max/mdev = 9.605/26.016/1459.616/60.821 ms, pipe 6

Test 1 North TC



APPENDIX "A"

South Tag Results

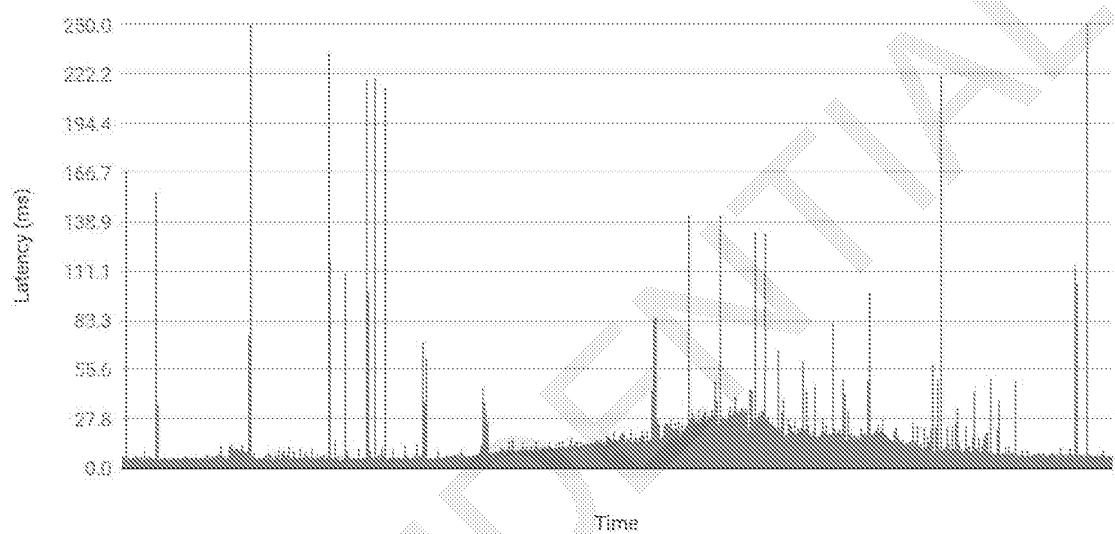
One-Way Latency: Min: 4.4ms / Avg: 16.4ms / Max: 694ms

Ping Summary:

1363 packets transmitted, 1339 received, 1% packet loss, time 341644ms

rtt min/avg/max/mdev = 8.721/32.730/1388.113/64.216 ms, pipe 6

Test 1 South TC



APPENDIX "A"

Test 2

7th to Church SB ATO 10 MPH

Start: 16:43 UTC

End: 16:56 UTC

North Tag Results

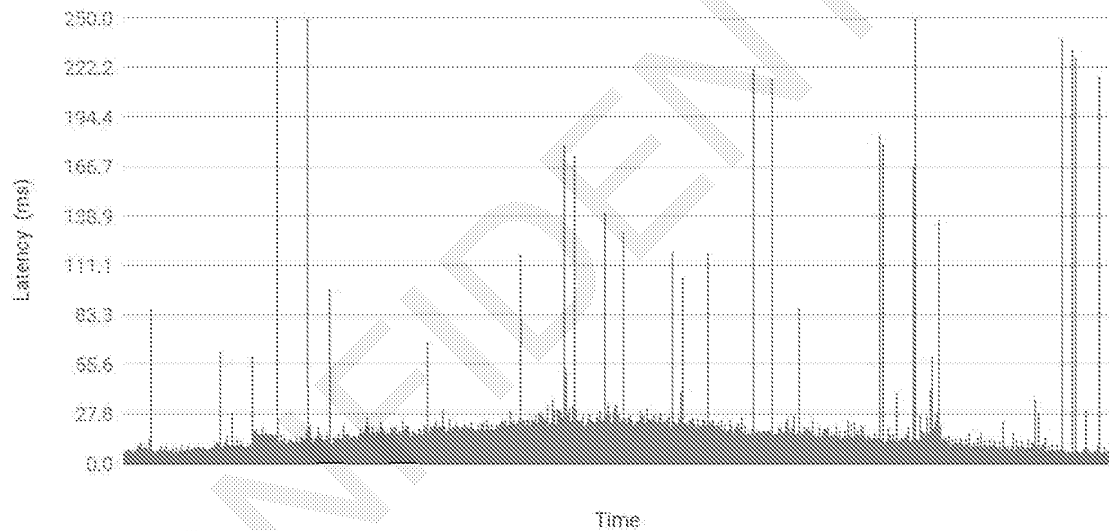
One-Way Latency: Min: 4.9ms / Avg: 17.7ms / Max: 914ms

Ping Summary:

2452 packets transmitted, 2413 received, 1% packet loss, time 614833ms

rtt min/avg/max/mdev = 9.798/35.399/1828.898/63.469 ms, pipe 8

Test 2 North TC



APPENDIX "A"

South Tag Results

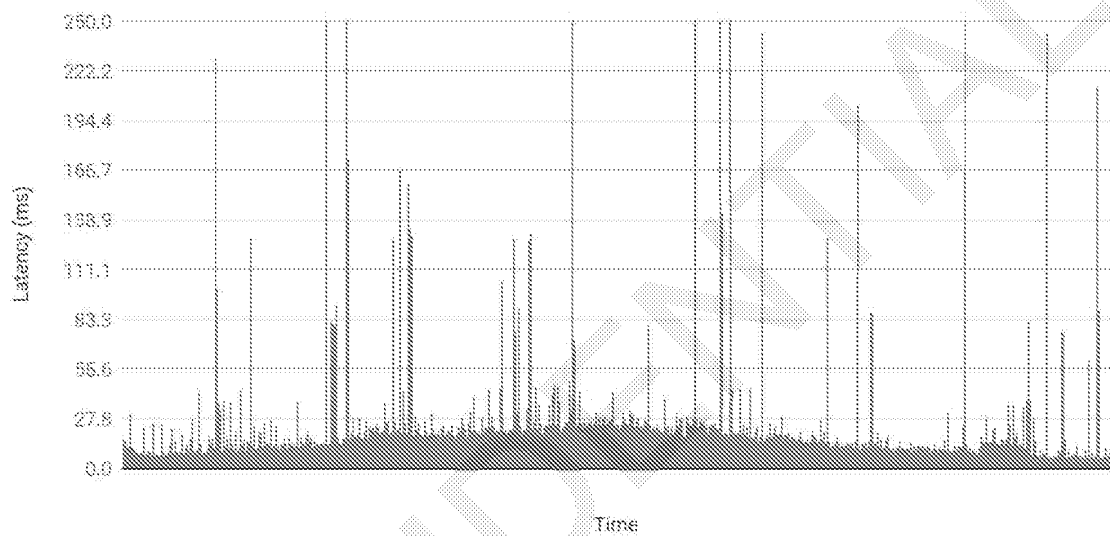
One-Way Latency: Min: 4.9ms / Avg: 18.6ms / Max: 421ms

Ping Summary:

2481 packets transmitted, 2445 received, 1% packet loss, time 622058ms

rtt min/avg/max/mdev = 9.771/37.161/841.961/51.354 ms, pipe 4

Test 2 South TC



APPENDIX "A"

Test 3

Church to 7th NB ATO

Start: 16:56 UTC

End: 17:04 UTC

North Tag Results

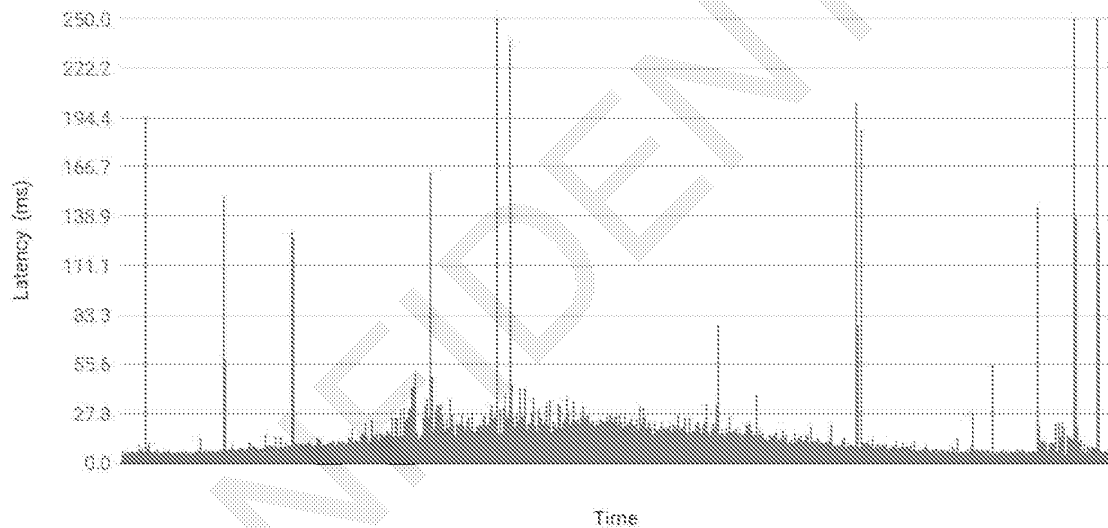
One-Way Latency: Min: 4.9ms / Avg: 17.2ms / Max: 261ms

Ping Summary:

1005 packets transmitted, 984 received, 2% packet loss, time 251889ms

rtt min/avg/max/mdev = 9.683/34.441/522.166/46.573 ms, pipe 3

Test 3 North TC



APPENDIX "A"

South Tag Results

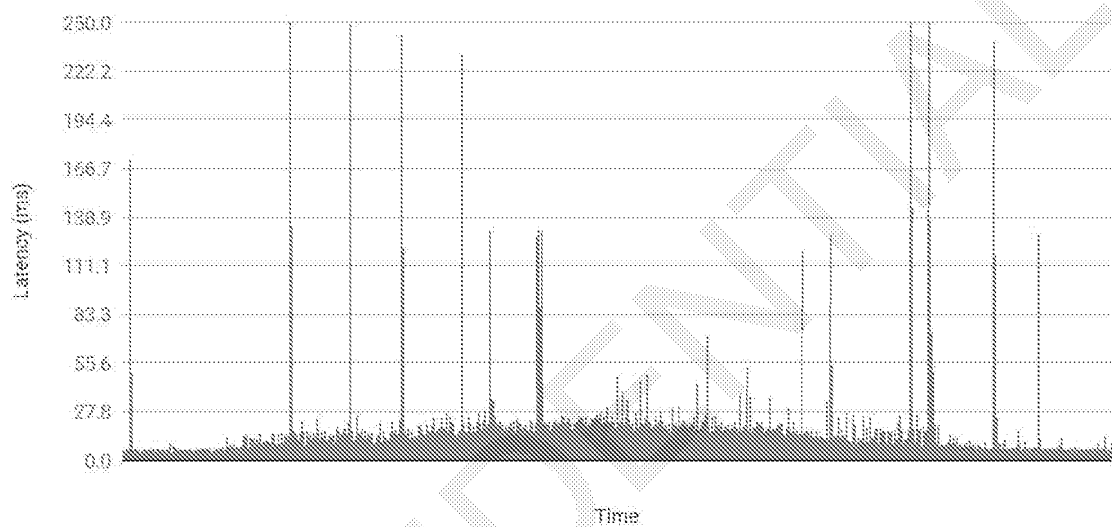
One-Way Latency: Min: 4.4ms / Avg: 18.5ms / Max: 264ms

Ping Summary:

933 packets transmitted, 914 received, 2% packet loss, time 233866ms

rtt min/avg/max/mdev = 8.862/37.063/529.133/52.032 ms, pipe 3

Test 3 South TC



APPENDIX "A"

Test 4

7th to Church SB manual 10 MPH

Start: 17:04 UTC

End: 17:17 UTC

North Tag Results

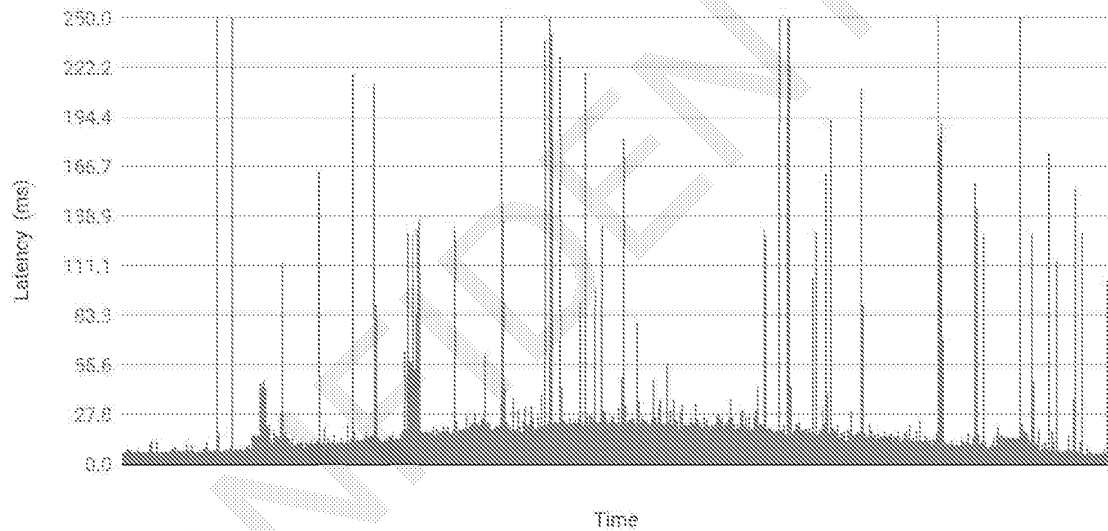
One-Way Latency: Min: 4.8ms / Avg: 19.2ms / Max: 500ms

Ping Summary:

2717 packets transmitted, 2684 received, 1% packet loss, time 681357ms

rtt min/avg/max/mdev = 9.641/38.491/999.534/58.477 ms, pipe 4

Test 4 North TC



APPENDIX "A"

South Tag Results

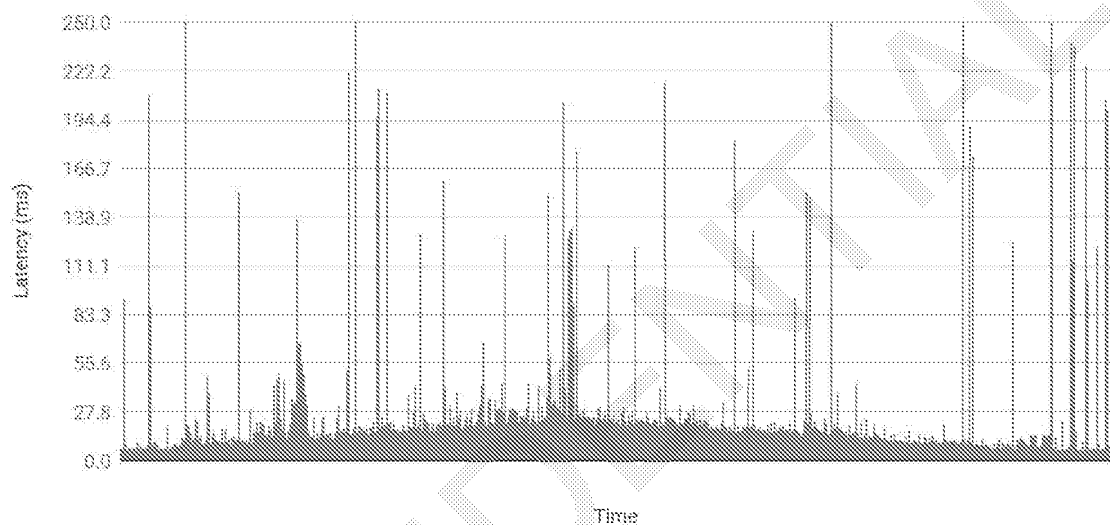
One-Way Latency: Min: 4.5ms / Avg: 19.5ms / Max: 1213ms

Ping Summary:

2661 packets transmitted, 2607 received, 2% packet loss, time 667342ms

rtt min/avg/max/mdev = 9.009/39.129/2426.700/80.522 ms, pipe 10

Test 4 South TC



APPENDIX "A"

Test 5

Church to 7th NB ATO SSO 29 MPH > 19 MPH > 29 MPH

Start: 17:27 UTC

End: 17:32 UTC

North Tag Results

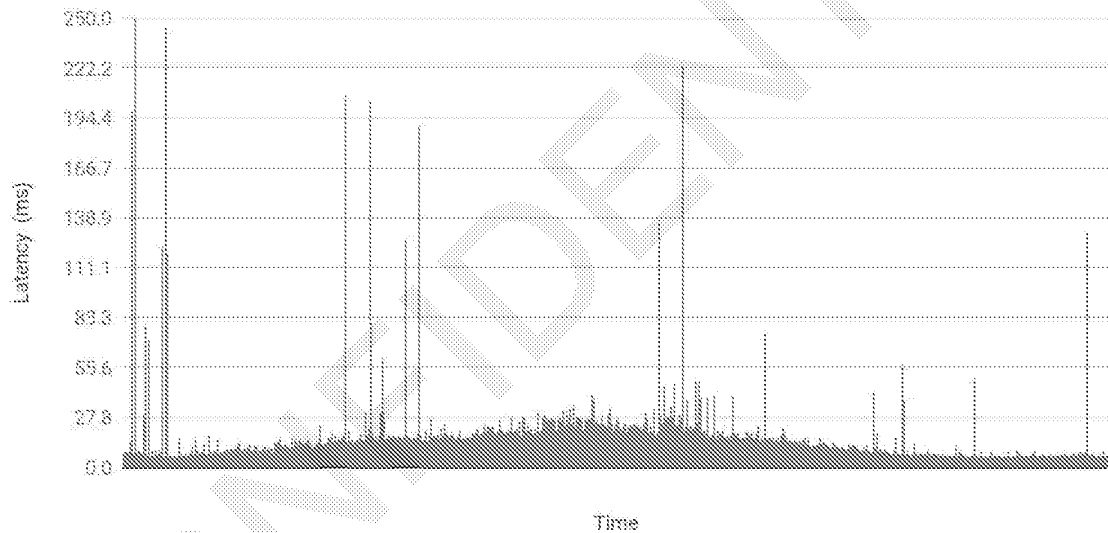
One-Way Latency: Min: 5.3ms / Avg: **16.3ms** / Max: 260ms

Ping Summary:

1213 packets transmitted, 1190 received, 1% packet loss, time 304073ms

rtt min/avg/max/mdev = 10.652/32.666/520.237/39.552 ms, pipe 3

Test 5 North TC



APPENDIX "A"

South Tag Results

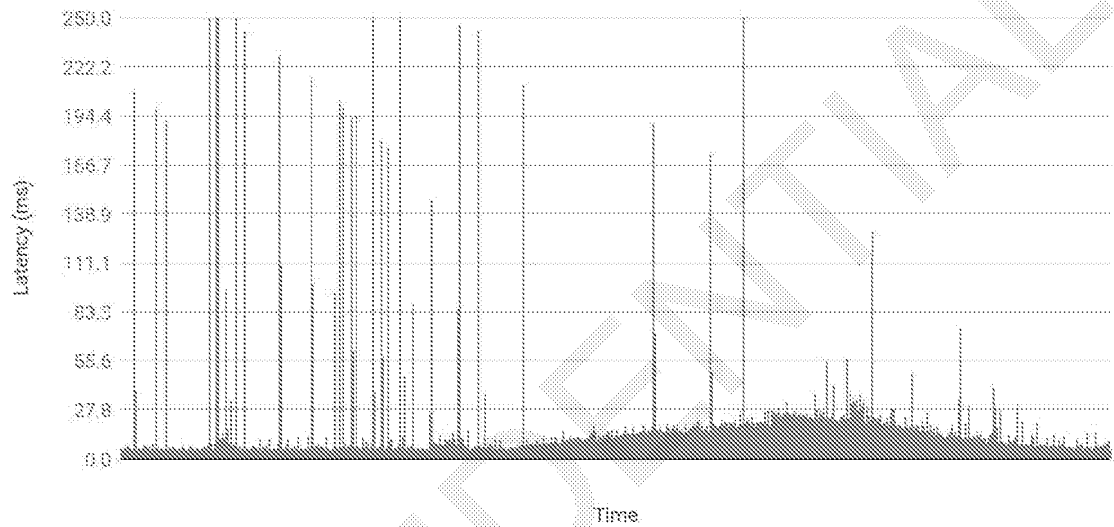
One-Way Latency: Min: 4.4ms / Avg: 18.3ms / Max: 1164ms

Ping Summary:

1712 packets transmitted, 1661 received, 2% packet loss, time 429436ms

rtt min/avg/max/mdev = 8.795/36.581/2328.199/105.061 ms, pipe 10

Test 5 South TC



APPENDIX "A"

Test 6

7th to church ATPM SB from VOBC2

Start: 17:43 UTC

End: 17:54 UTC

North Tag Results

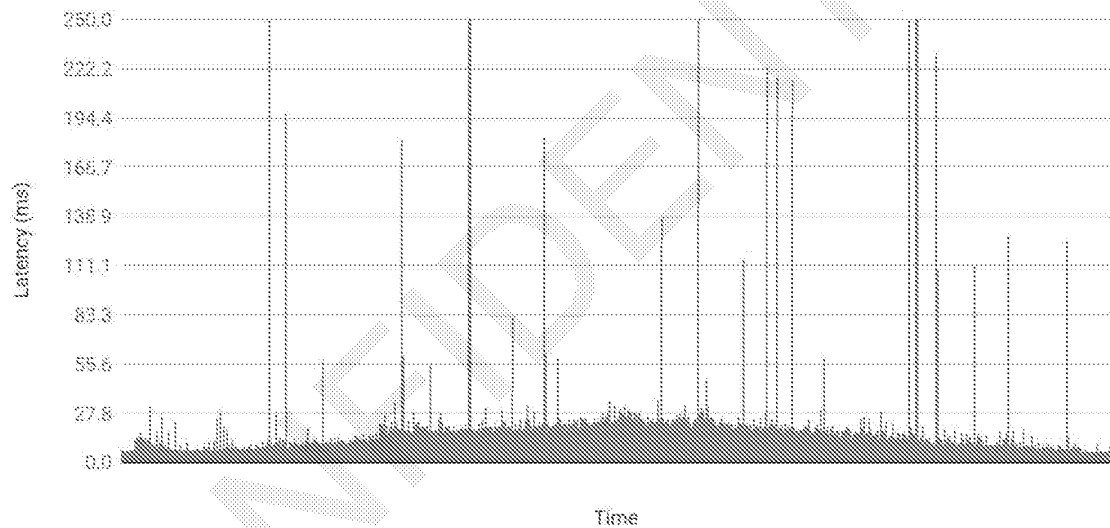
One-Way Latency: Min: 4.8ms / Avg: 18.2ms / Max: 1424ms

Ping Summary:

2644 packets transmitted, 2598 received, 1% packet loss, time 663008ms

rtt min/avg/max/mdev = 9.673/36.455/2848.528/101.748 ms, pipe 12

Test 6 North TC



APPENDIX "A"

South Tag Results

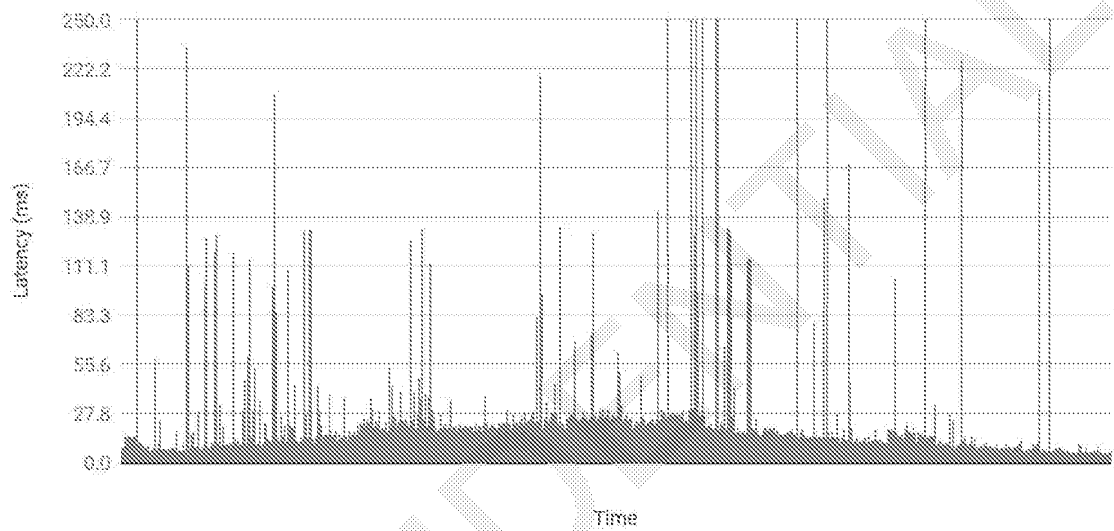
One-Way Latency: Min: 4.5ms / Avg: 19.8ms / Max: 749ms

Ping Summary:

2611 packets transmitted, 2578 received, 1% packet loss, time 654747ms

rtt min/avg/max/mdev = 9.061/39.639/1498.866/71.566 ms, pipe 6

Test 6 South TC



APPENDIX "A"

Test 7

Church to 7th NB ATPM 29 MPH

Start: 18:14 UTC

End: 18:18 UTC

North Tag Results

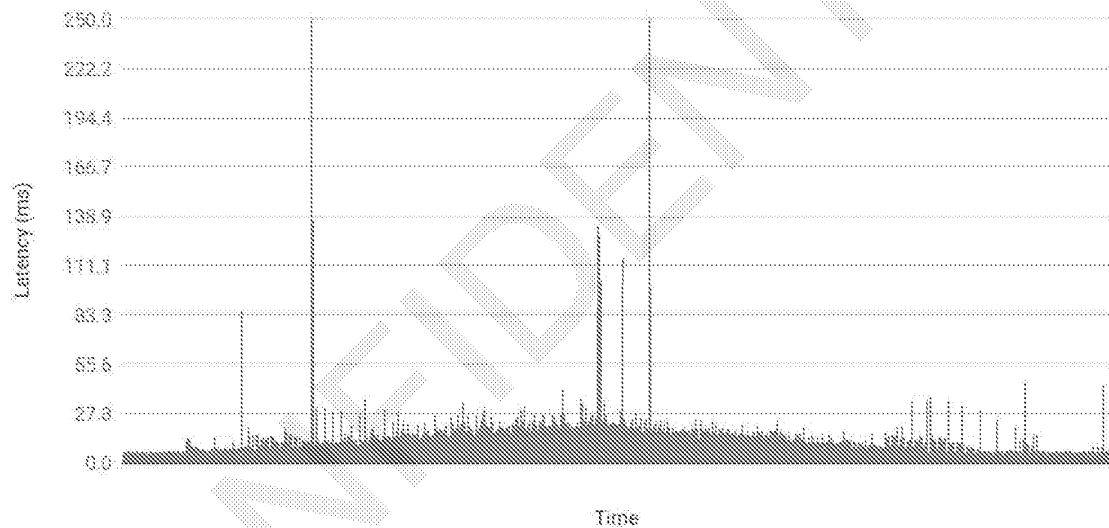
One-Way Latency: Min: 5.0ms / Avg: **15.6ms** / Max: 337ms

Ping Summary:

999 packets transmitted, 978 received, 2% packet loss, time 250354ms

rtt min/avg/max/mdev = 9.981/31.196/674.597/36.205 ms, pipe 3

Test 7 North TC



APPENDIX "A"

South Tag Results

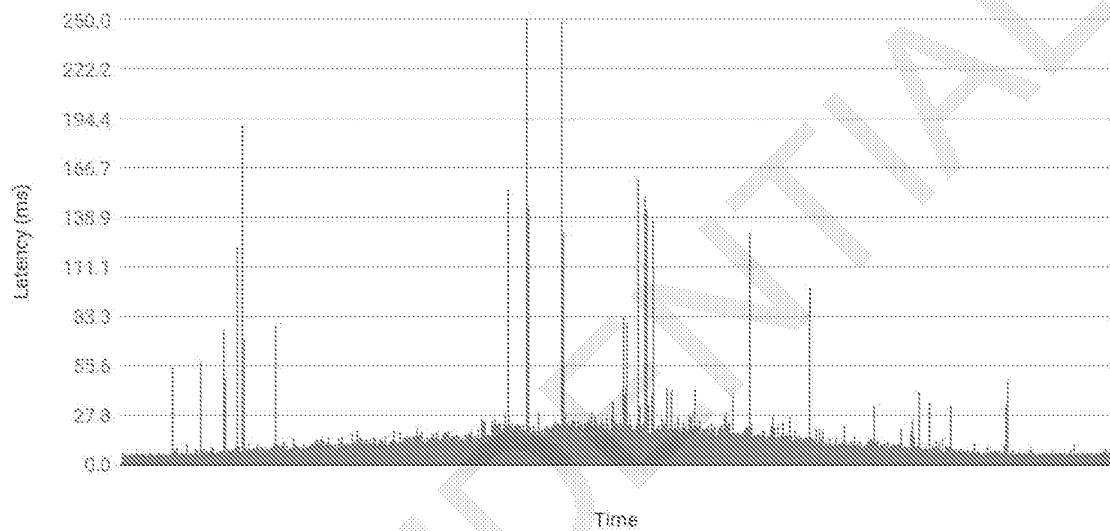
One-Way Latency: Min: 4.9ms / Avg: 16.5ms / Max: 267ms

Ping Summary:

916 packets transmitted, 902 received, 1% packet loss, time 229558ms

rtt min/avg/max/mdev = 9.820/33.073/533.942/40.413 ms, pipe 3

Test 7 South TC



APPENDIX "A"

Test 8

7th to Church SB ATO 10MPH VOBC2

Start: 18:22 UTC

End: 18:35 UTC

North Tag Results

One-Way Latency: Min: 5.1ms / Avg: **18.5ms** / Max: 682ms

Ping Summary: (note that ping was interrupted and resumed, so both summaries are shown)

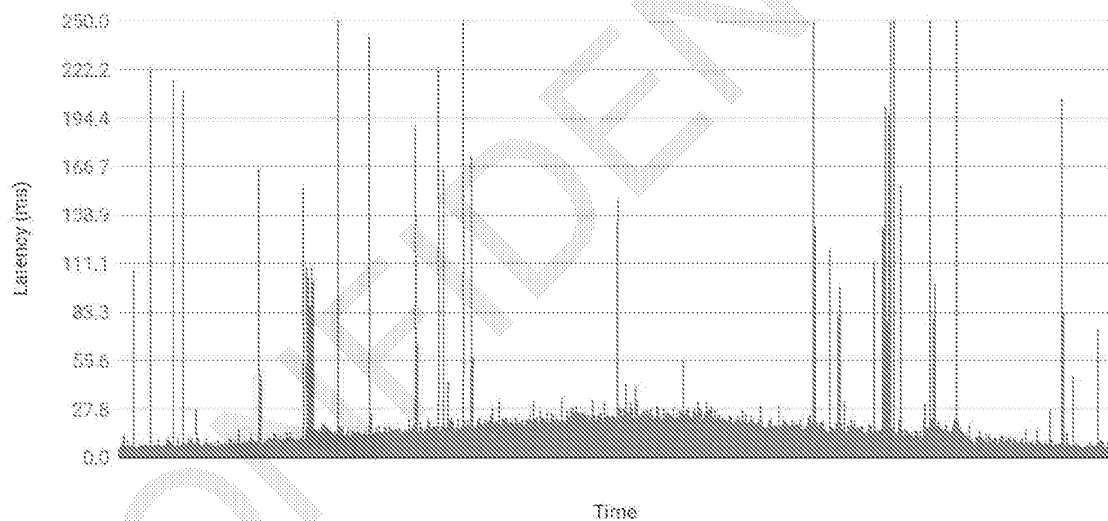
1748 packets transmitted, 1672 received, 4% packet loss, time 438461ms

rtt min/avg/max/mdev = 10.406/37.118/651.142/41.375 ms, pipe 3

753 packets transmitted, 736 received, 2% packet loss, time 188749ms

rtt min/avg/max/mdev = 10.195/36.151/1364.715/89.467 ms, pipe 6

Test 8 North TC



APPENDIX "A"

South Tag Results

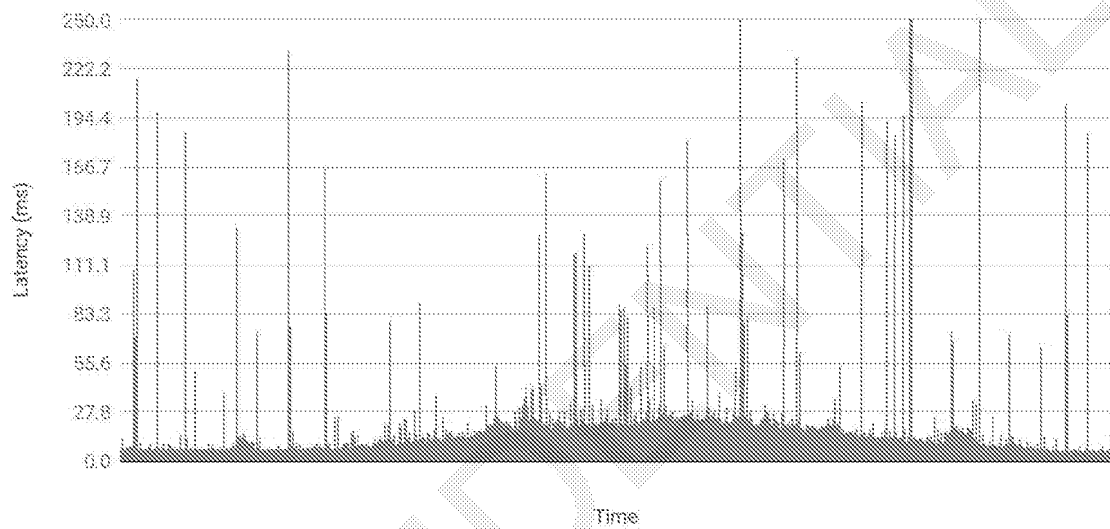
One-Way Latency: Min: 4.7ms / Avg: 16.2ms / Max: 518ms

Ping Summary:

3052 packets transmitted, 2986 received, 2% packet loss, time 765383ms

rtt min/avg/max/mdev = 9.476/32.473/1036.664/47.389 ms, pipe 5

Test 8 South TC



APPENDIX "A"

Test 9

7th to Church SB ATO

Start: 19:05 UTC

End: 19:19 UTC

North Tag Results

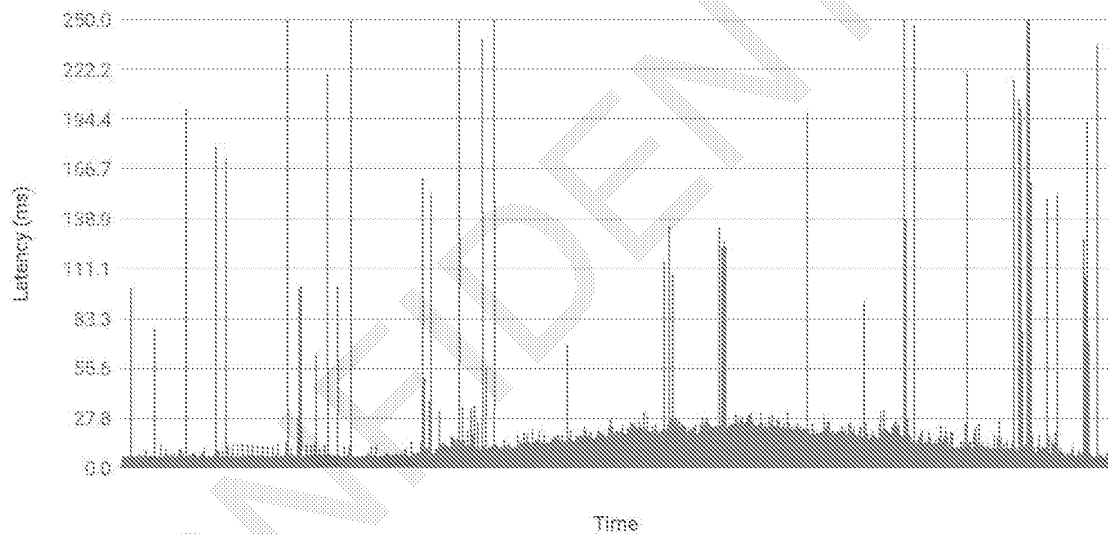
One-Way Latency: Min: 5.1ms / Avg: 16.4ms / Max: 960ms

Ping Summary:

3305 packets transmitted, 3246 received, 1% packet loss, time 828861ms

rtt min/avg/max/mdev = 10.270/32.848/1921.060/74.715 ms, pipe 8

Test 9 North TC



APPENDIX "A"

South Tag Results

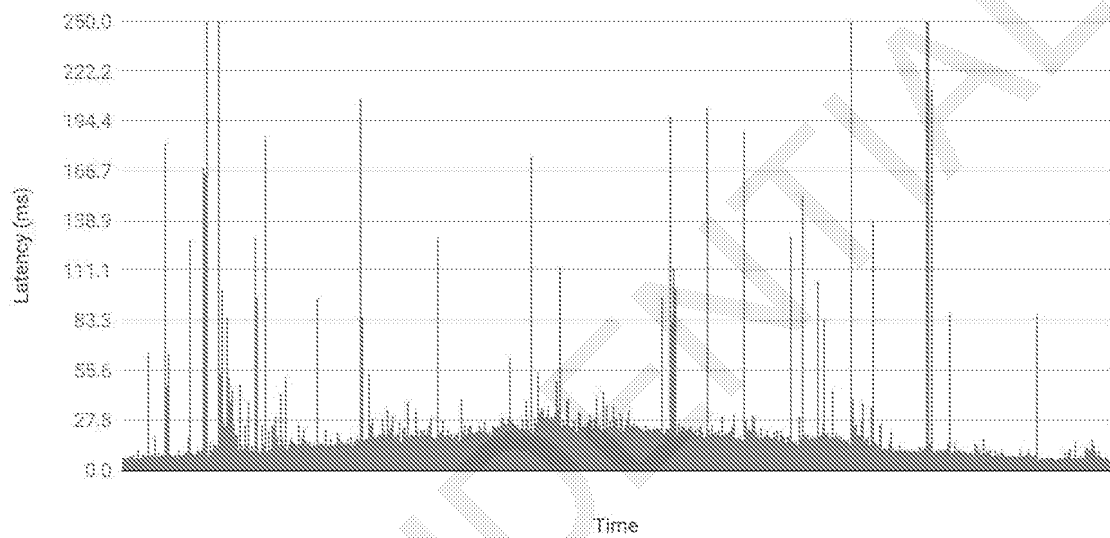
One-Way Latency: Min: 4.7ms / Avg: 18.2ms / Max: 619ms

Ping Summary:

2511 packets transmitted, 2465 received, 1% packet loss, time 629622ms

rtt min/avg/max/mdev = 9.427/36.484/1238.060/53.748 ms, pipe 5

Test 9 South TC



APPENDIX "A"

Test 10

Church to 7th NB ATO

Start: 19:21 UTC

End: 19:26 UTC

North Tag Results

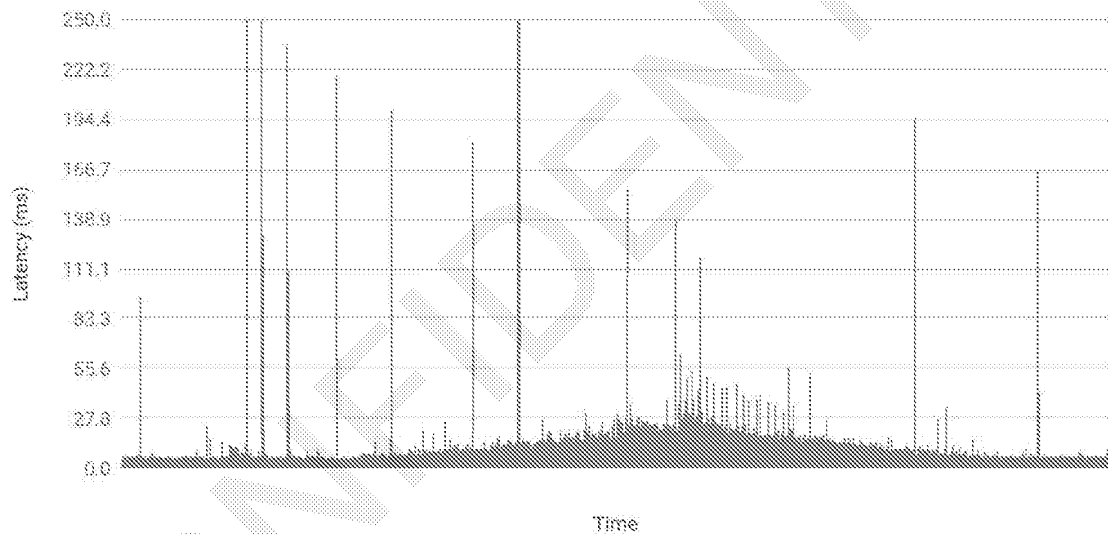
One-Way Latency: Min: 4.7ms / Avg: 15.3ms / Max: 649ms

Ping Summary:

1262 packets transmitted, 1236 received, 2% packet loss, time 316394ms

rtt min/avg/max/mdev = 9.481/30.579/1297.210/61.231 ms, pipe 6

Test 10 North TC



APPENDIX "A"

South Tag Results

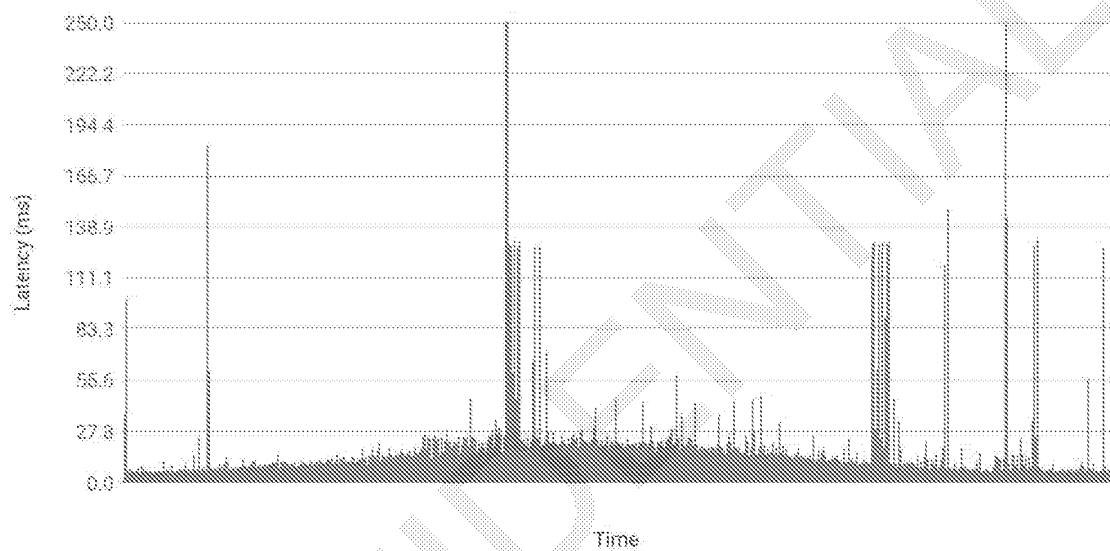
One-Way Latency: Min: 5.4ms / Avg: 19.6ms / Max: 507ms

Ping Summary:

954 packets transmitted, 935 received, 1% packet loss, time 239146ms

rtt min/avg/max/mdev = 10.801/39.248/1014.028/63.175 ms, pipe 4

Test 10 South TC



Data Visualization

Ranging Tests:

All distances in meters along the track from the Thales-defined zero point.



Raw Tag-to-Anchor distances for all 10 tests from the south tag (including manual run past 7th).

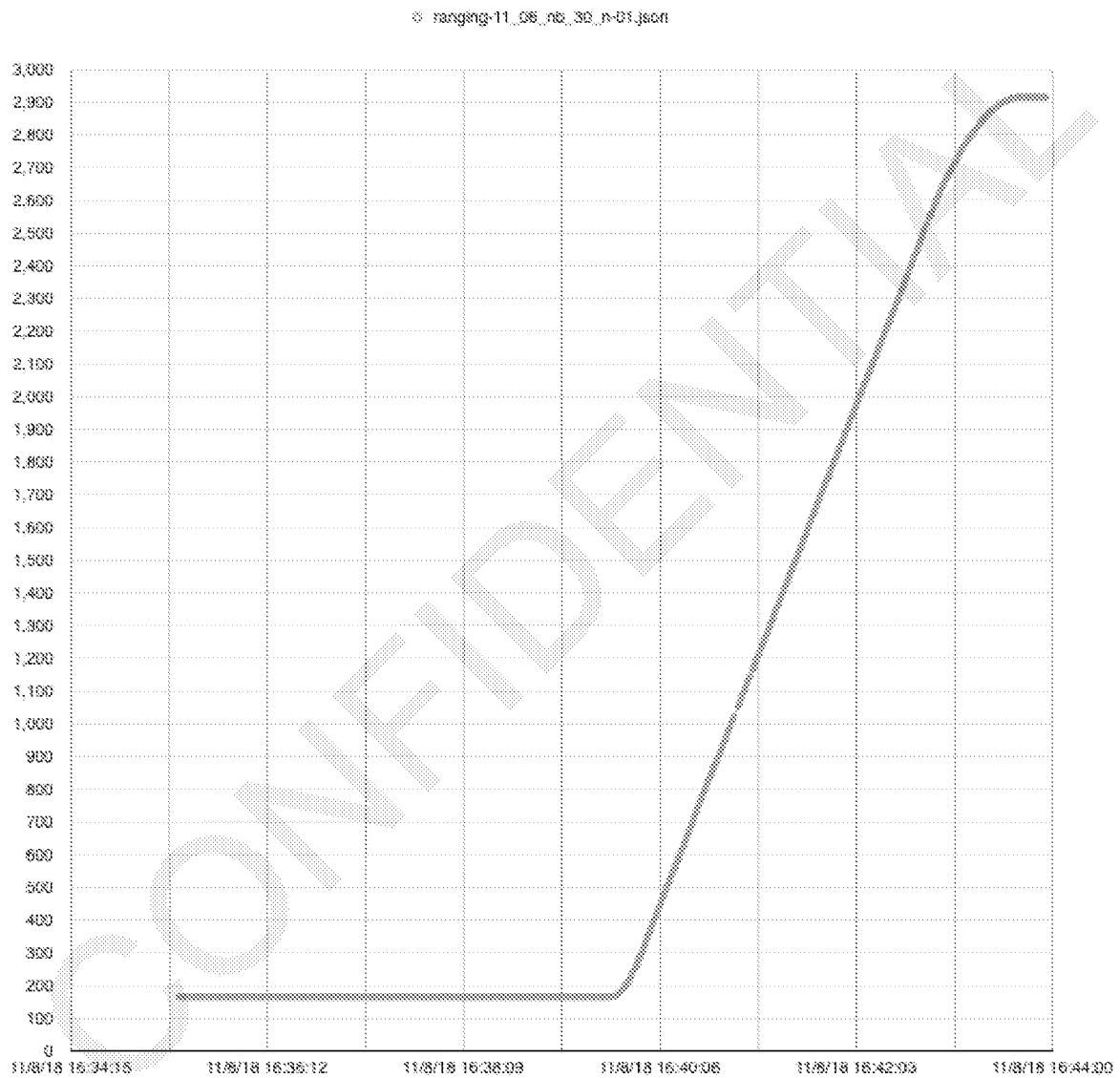
Note that on the right side of the graph, the points running off the top is due to an occasion where the train rolled through 7th and went on to 4th, past the range of anchors. Horizontal gaps correspond to times between the test runs.

The following graphs were created by plotting the computed position of the tag using the raw ranging data in the specified file. The "Location success" number is computed by dividing the number of successful location computations by the number of ranging sets valid for the computation.

Some gaps may appear in the ranging data for a given tag for a given run. Note that looking at data from the opposite tag on the same run typically does not have the same gaps - in other words, conflating the data from both tags on a given run will providing a complete, uninterrupted stream of location data.

APPENDIX "A"

File: ranging-11_08_nb_30_n-01.json
Description: 30mph Northbound, North Tag Controller
Start: 08 Nov 2018 16:35:19 GMT
End: 08 Nov 2018 16:43:56 GMT
Location success: 1008/1019 = 98.92%



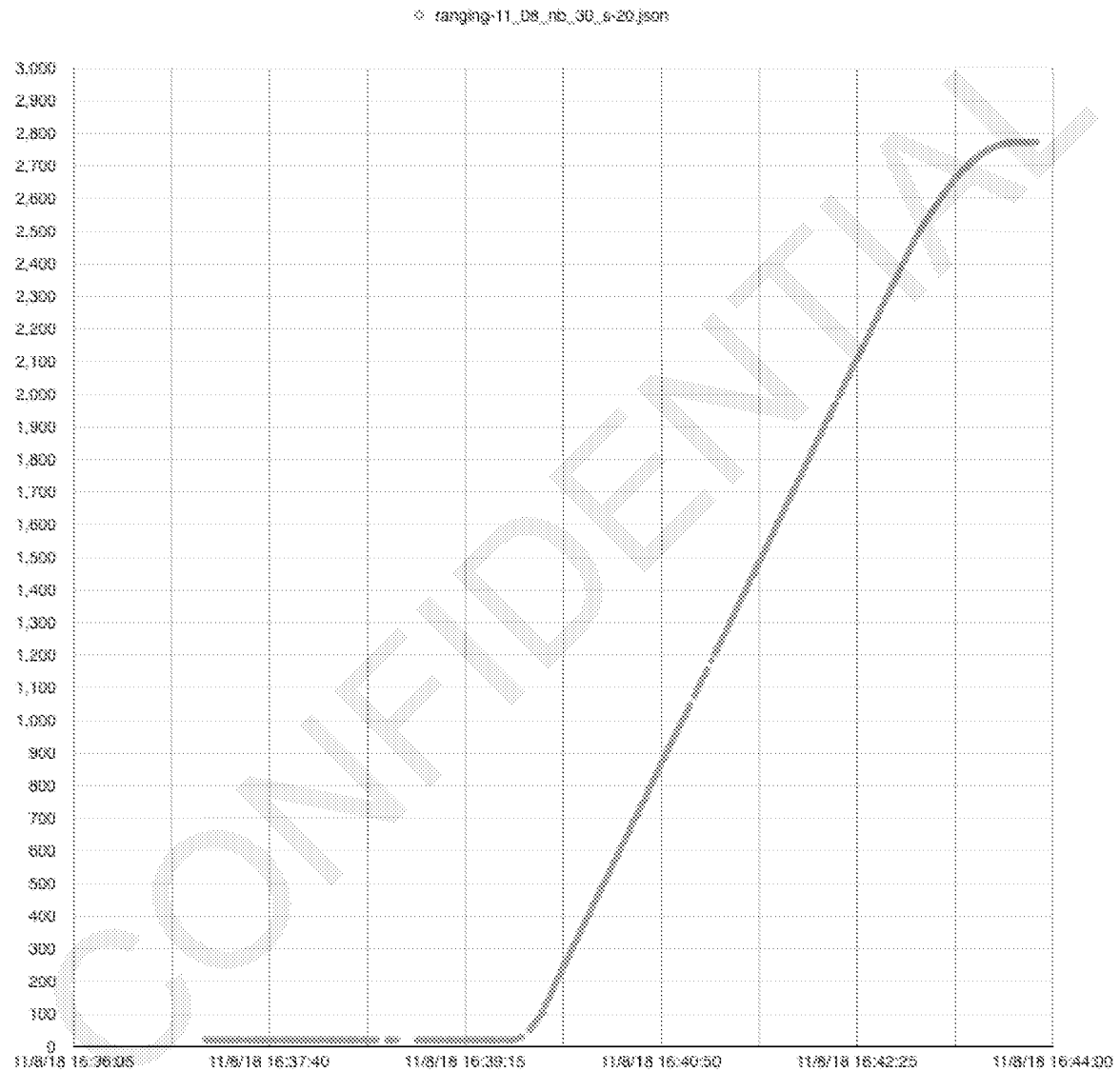
APPENDIX "A"

File: ranging-11_08_nb_30_s-20.json

Description: 30 mph Northbound, South Tag Controller

Start: 08 Nov 2018 16:37:09 GMT

End: 08 Nov 2018 16:43:42 GMT



APPENDIX "A"

File: ranging-11_08_sb_10_s-21.json

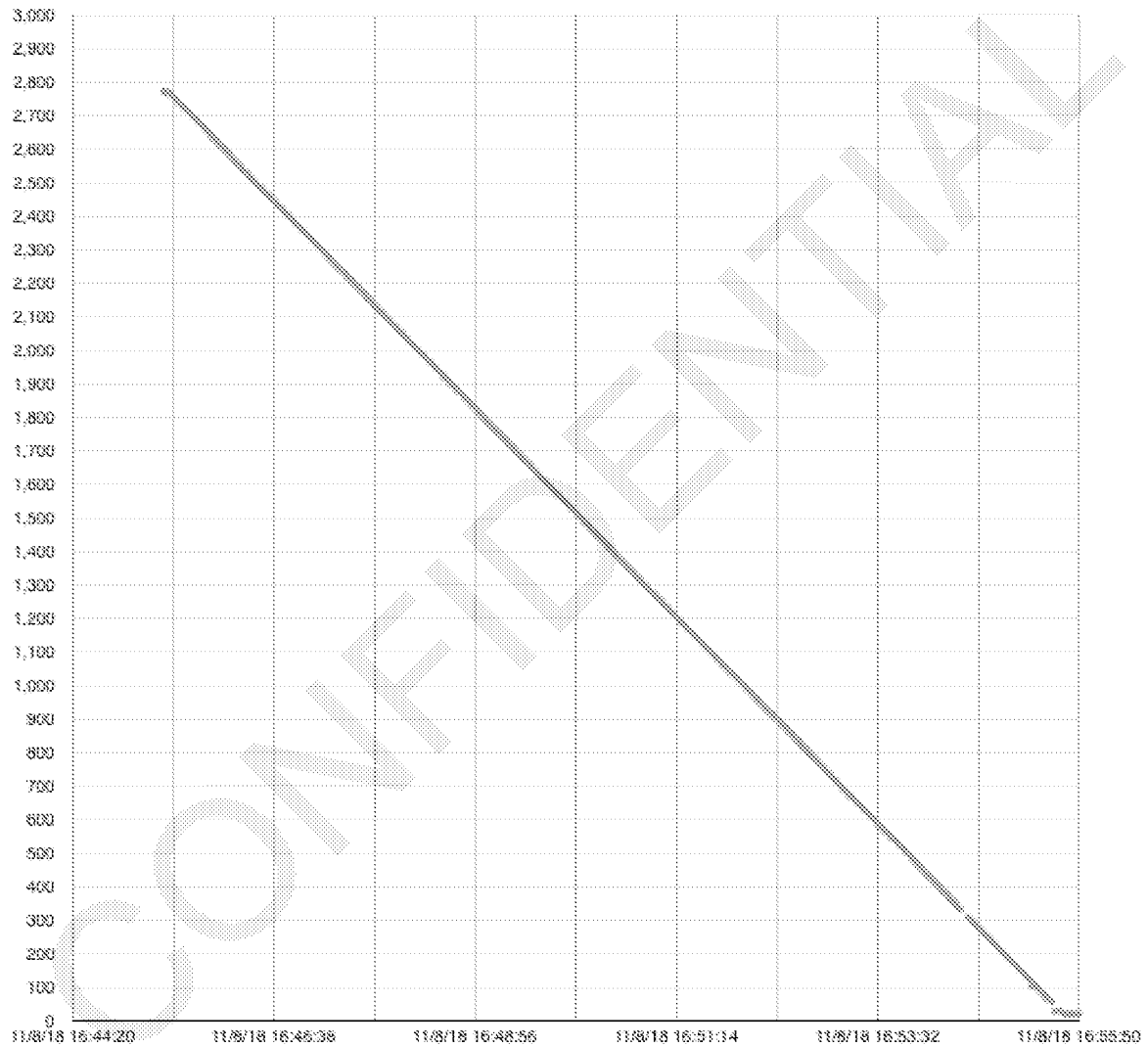
Description: 10mph Southbound, South Tag Controller

Start: 08 Nov 2018 16:45:22 GMT

End: 08 Nov 2018 16:55:50 GMT

Location success: 1182/1208 = 97.84%

◇ ranging-11_08_sb_10_s-21.json



APPENDIX "A"

File: ranging-11_06_sb_10_n-02.json

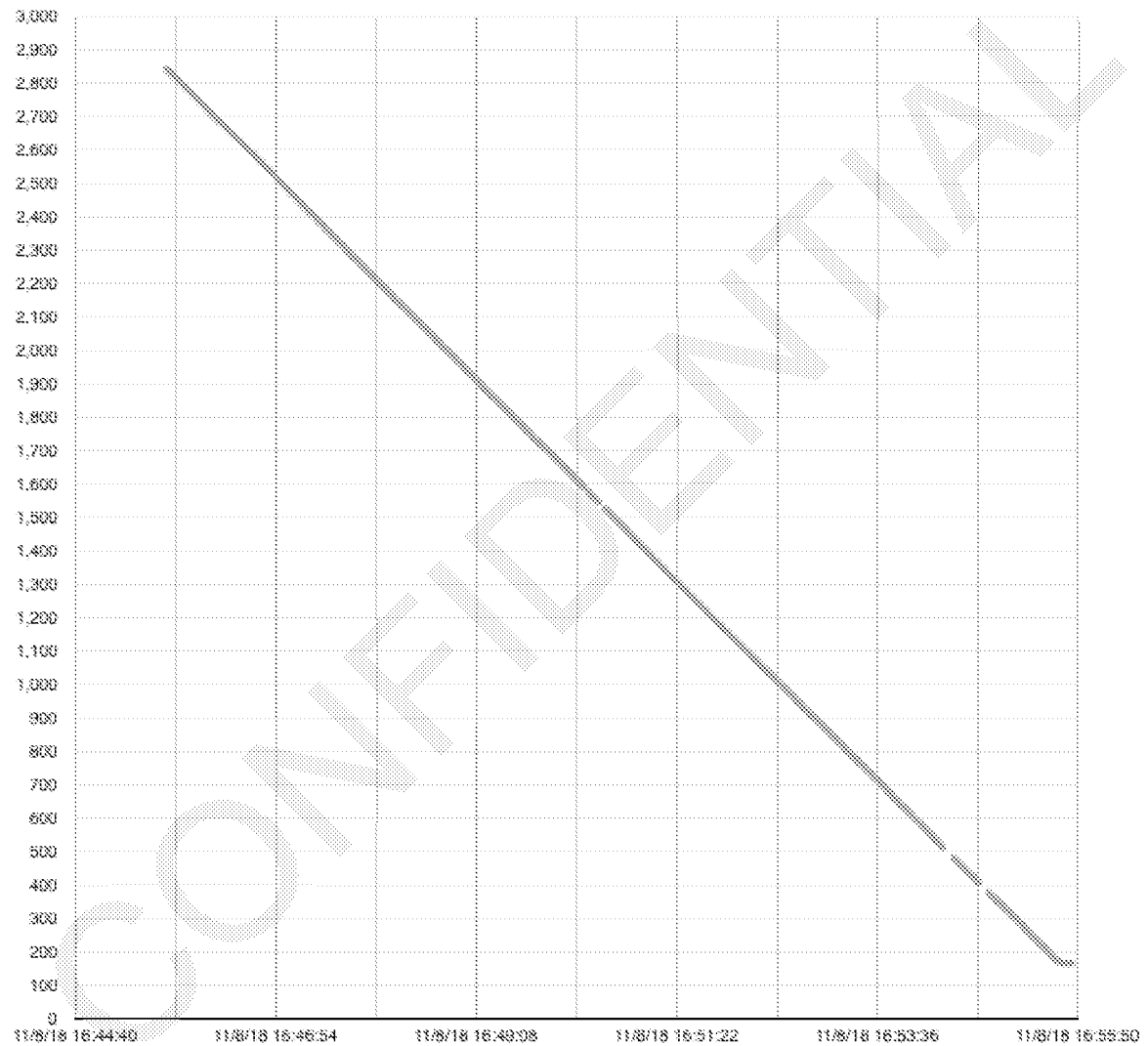
Description: 10mph Southbound, North Tag Controller

Start: 08 Nov 2018 16:45:41 GMT

End: 08 Nov 2018 16:55:46 GMT

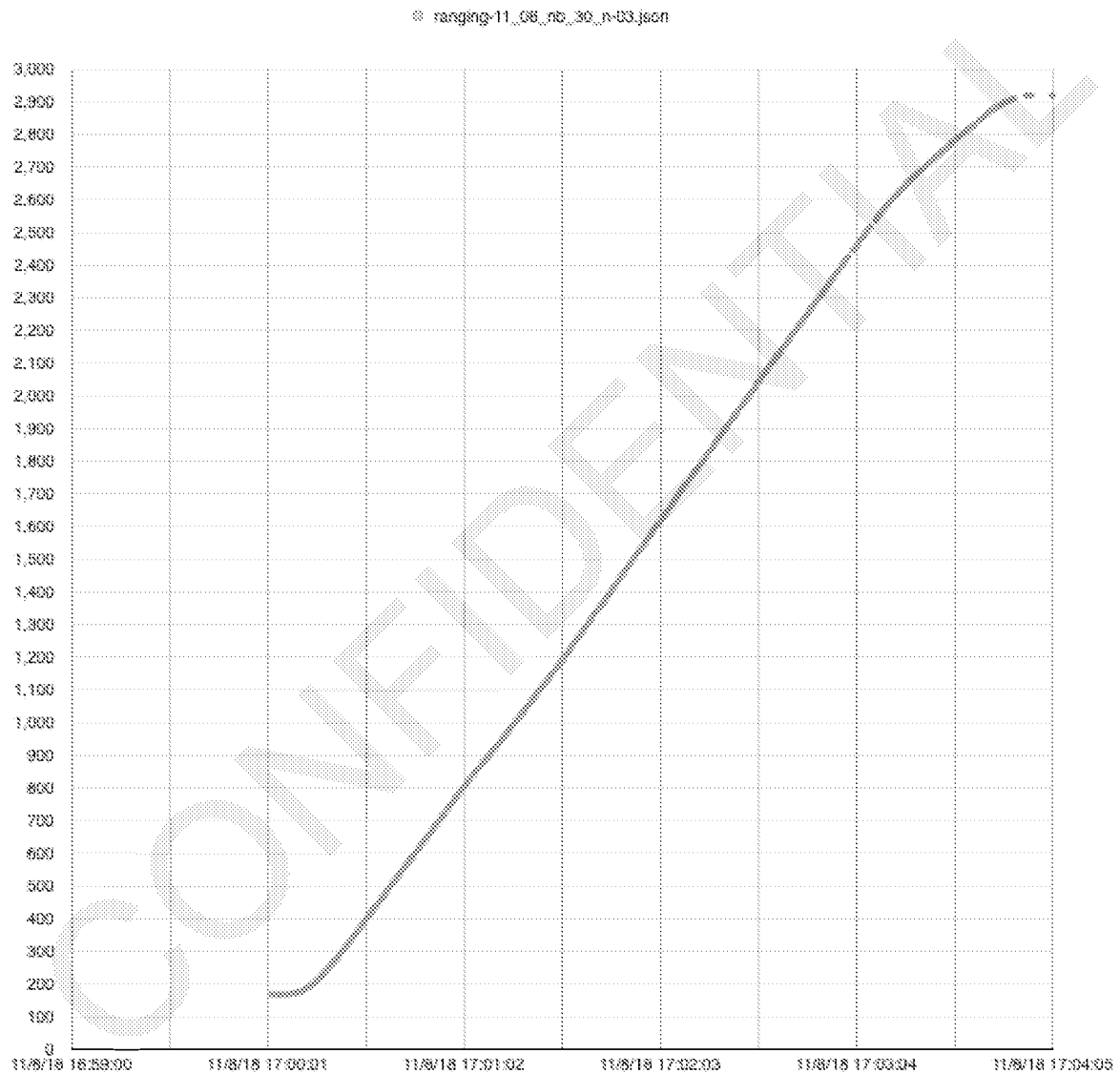
Location success: 1133/1153 = 98.26%

◇ ranging-11_06_sb_10_n-02.json



APPENDIX "A"

File: ranging-11_08_nb_30_n-03.json
Description: 30mph Northbound, North Tag Controller
Start: 08 Nov 2018 17:00:02 GMT
End: 08 Nov 2018 17:04:05 GMT
Location success: 452/459 = 98.47%



APPENDIX "A"

File: ranging-11_08_nb_30_n-22.json

Description: 30 mph Northbound, North Tag Controller

Start: 08 Nov 2018 17:00:11 GMT

End: 08 Nov 2018 17:04:02 GMT

Location success: 420/427 = 98.36%

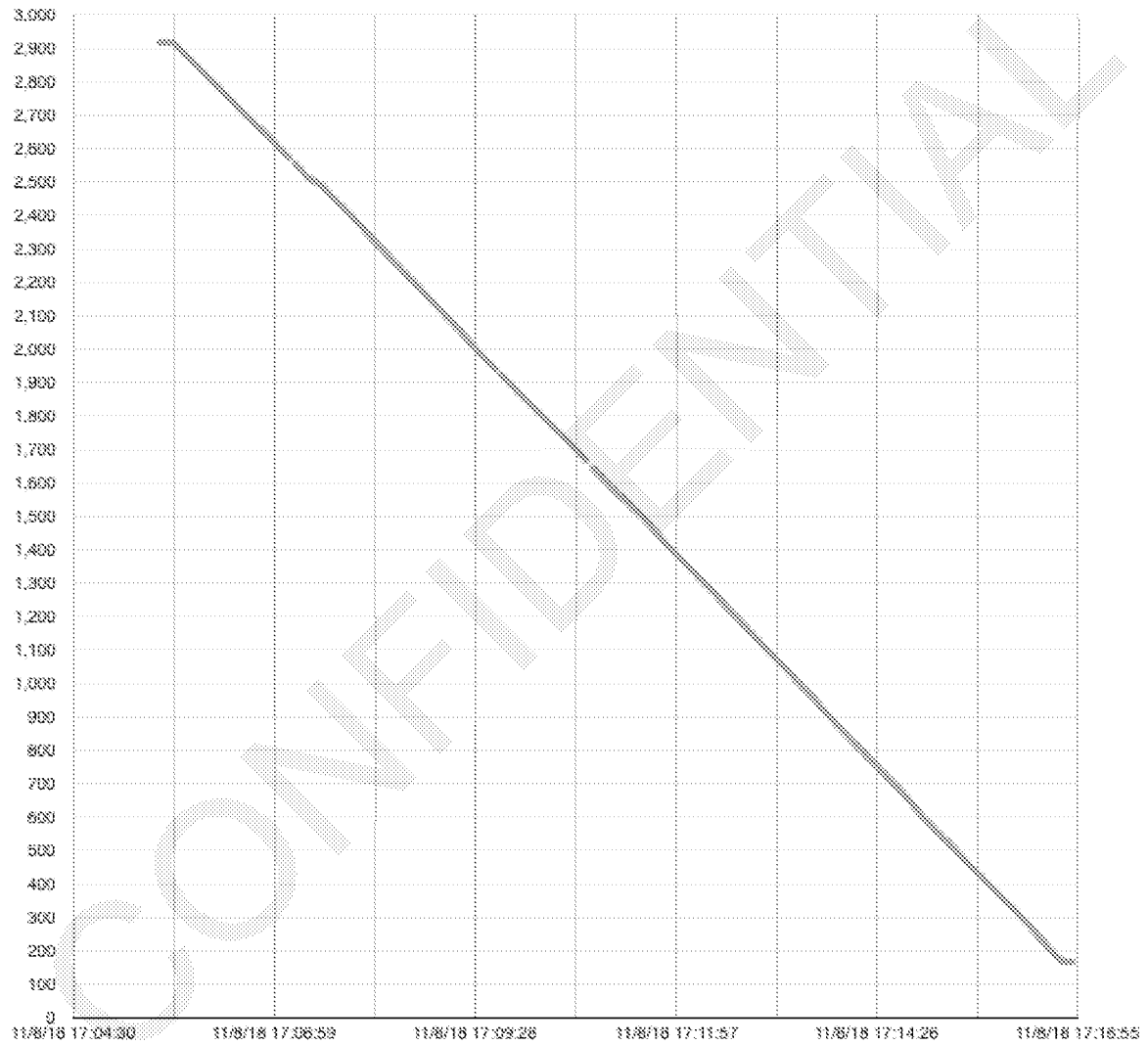
○ ranging-11_08_nb_30_n-22.json



APPENDIX "A"

File: ranging-11_08_sb_10_n-04.json
 Description: 10 mph Southbound, North Tag Controller
 Start: 08 Nov 2018 17:05:34 GMT
 End: 08 Nov 2018 17:16:51 GMT
 Location success: 98.31%

※ ranging-11_08_sb_10_n-04.json



APPENDIX "A"

File: ranging-11_08_sb_man_s-23.json

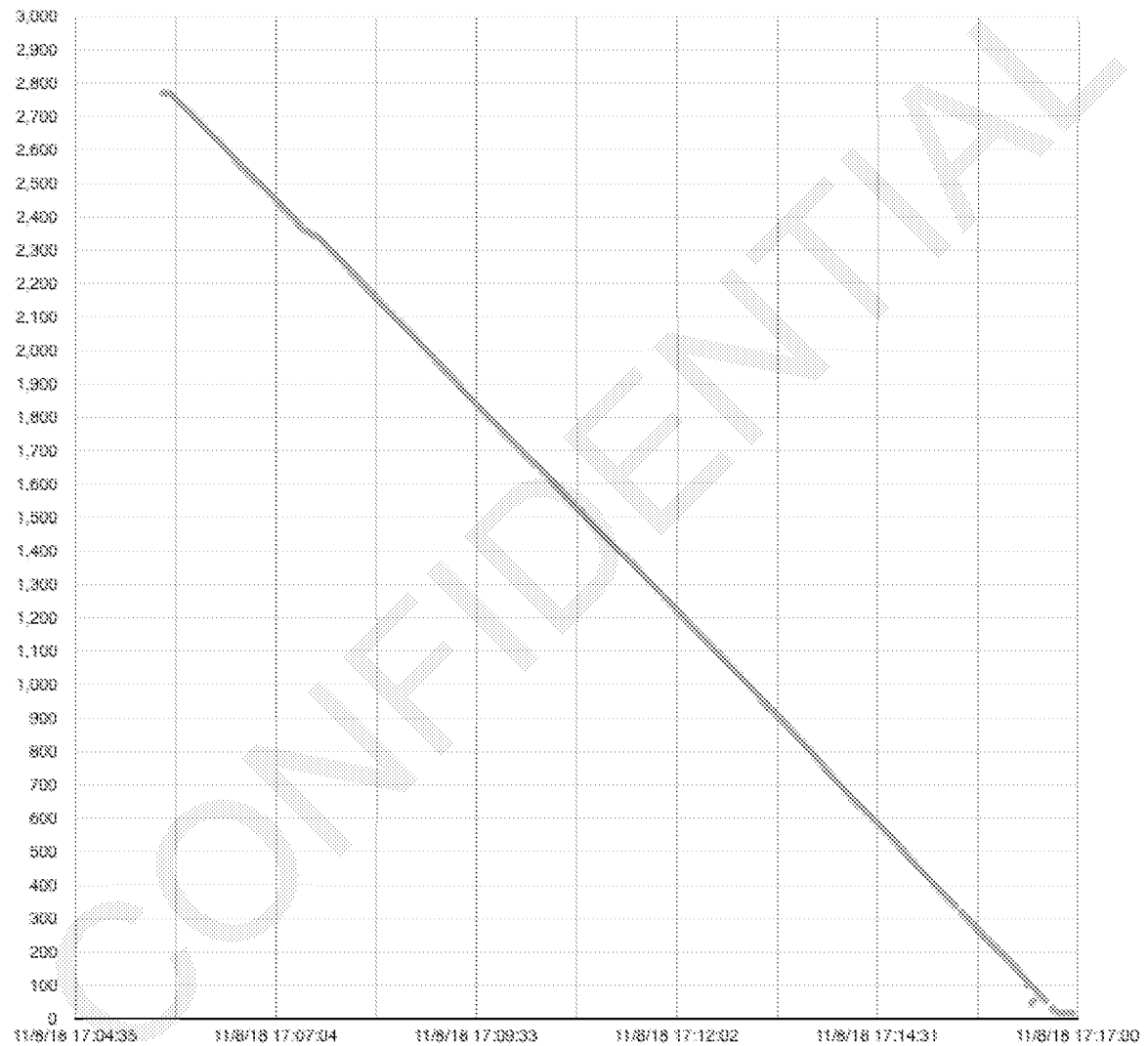
Description: Manual 10mph Southbound, South Tag Controller

Start: 08 Nov 2018 17:05:40 GMT

End: 08 Nov 2018 17:16:56 GMT

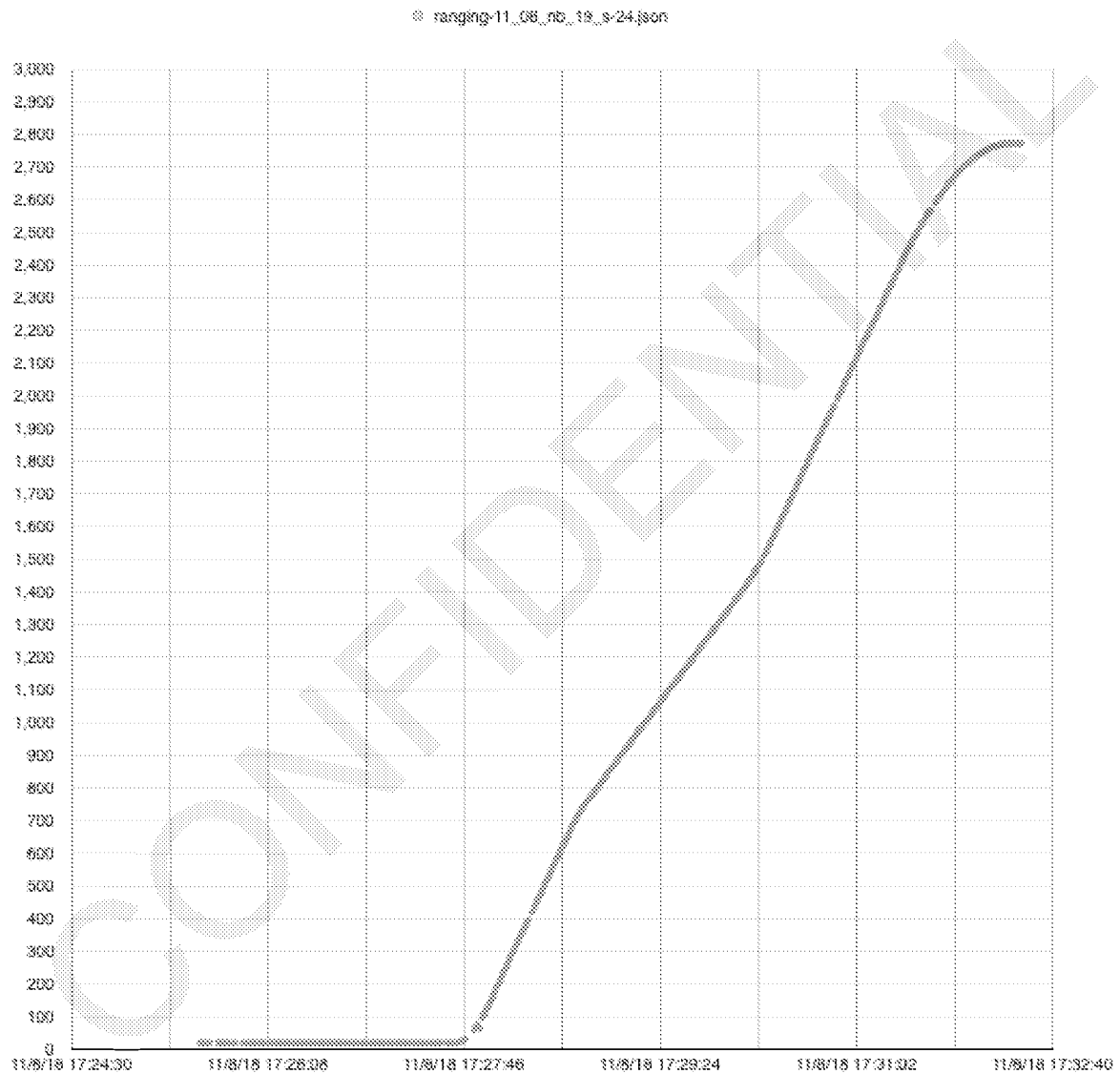
Location success: 1248/1279 = 97.57%

© ranging-11_08_sb_man_s-23.json



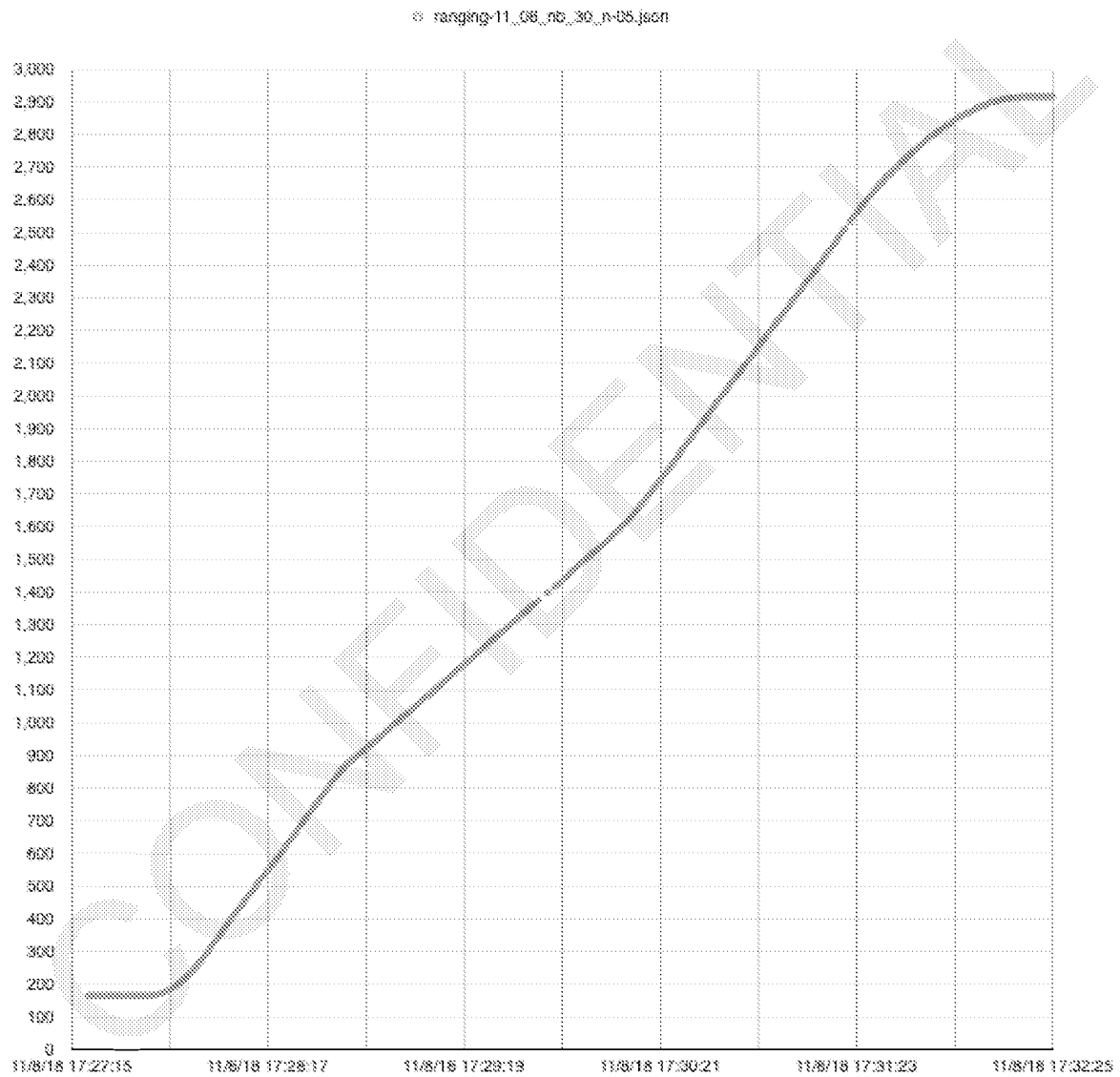
APPENDIX "A"

File: ranging-11_08_nb_19_s-24.json
 Description: 19mph Northbound, South Tag Controller
 Start: 08 Nov 2018 17:25:34 GMT
 End: 08 Nov 2018 17:32:24 GMT
 Location success: 692/734 = 94.27%



APPENDIX "A"

File: ranging-11:08_nb_30_n-05.json
 Description: 30mph Northbound, North Tag Controller
 Start: 08 Nov 2018 17:27:20 GMT
 End: 08 Nov 2018 17:32:35 GMT
 Location success: 584/591 = 98.81%



APPENDIX "A"

File: range-11_08_sb_30_n-06.json

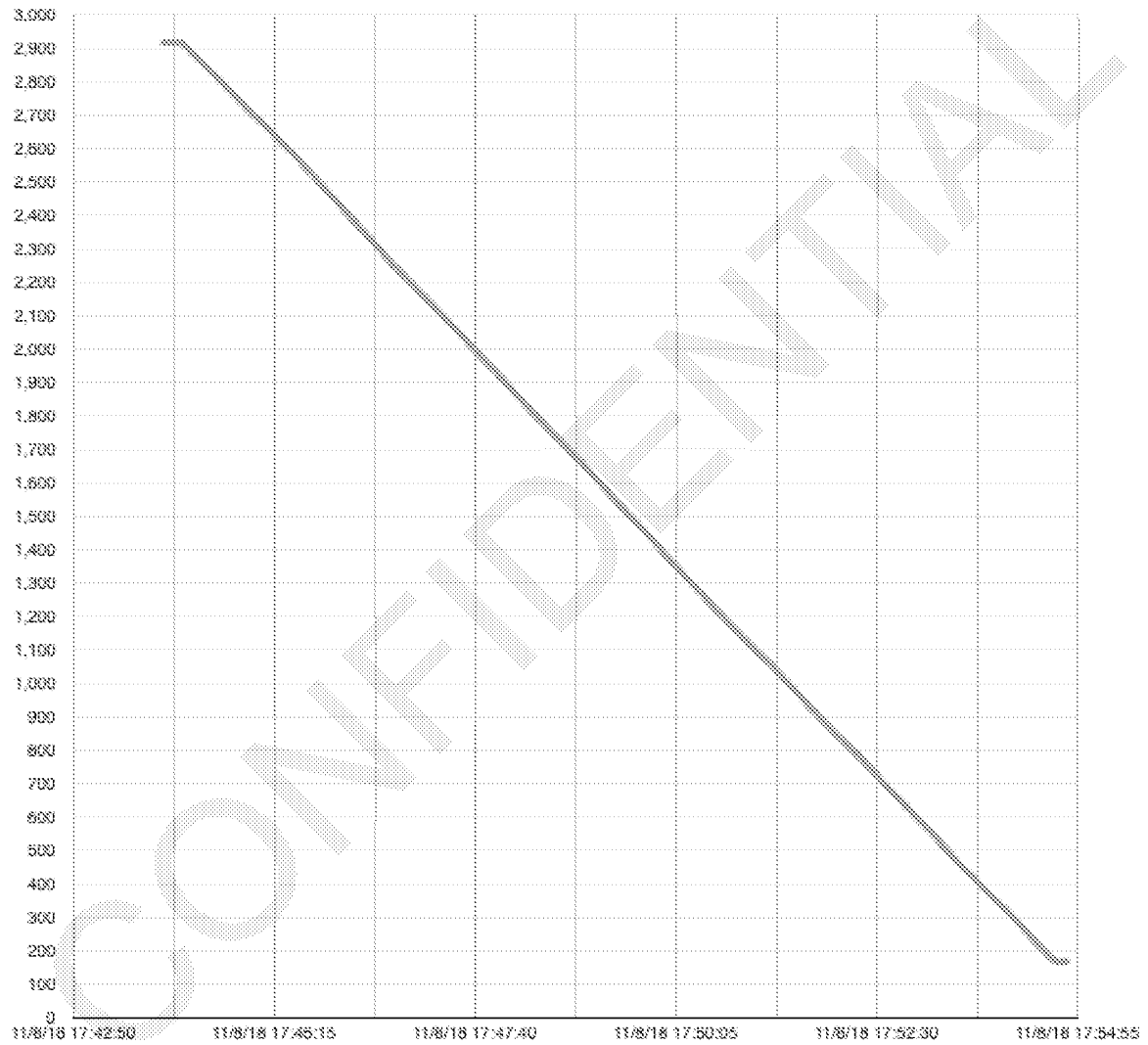
Description: 10 mph Southbound, North Tag Controller

Start: 08 Nov 2018 17:42:55 GMT

End: 08 Nov 2018 17:54:47 GMT

Location success: 1253/1274 = 98.35%

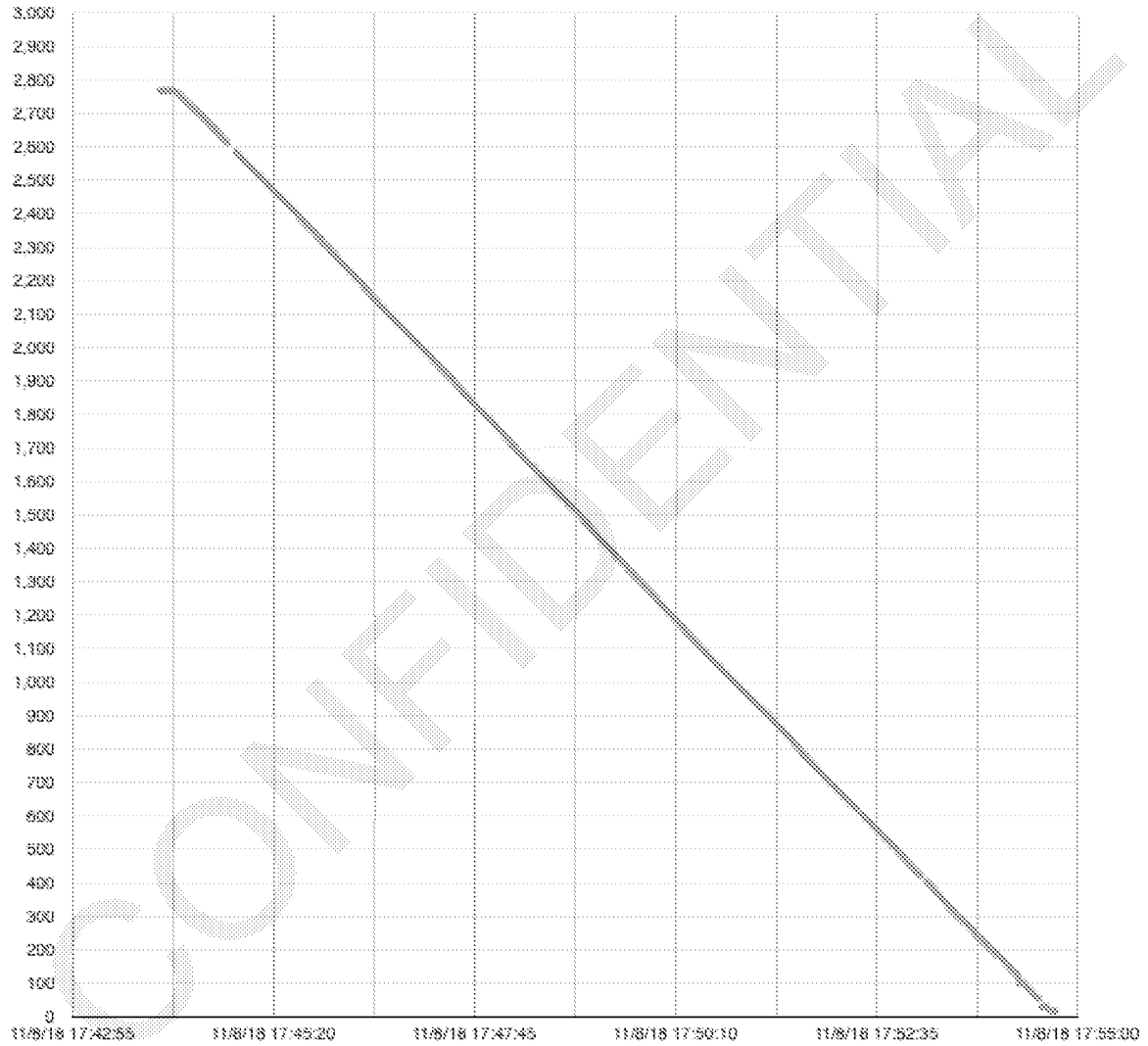
※ range-11_08_sb_30_n-06.json



APPENDIX "A"

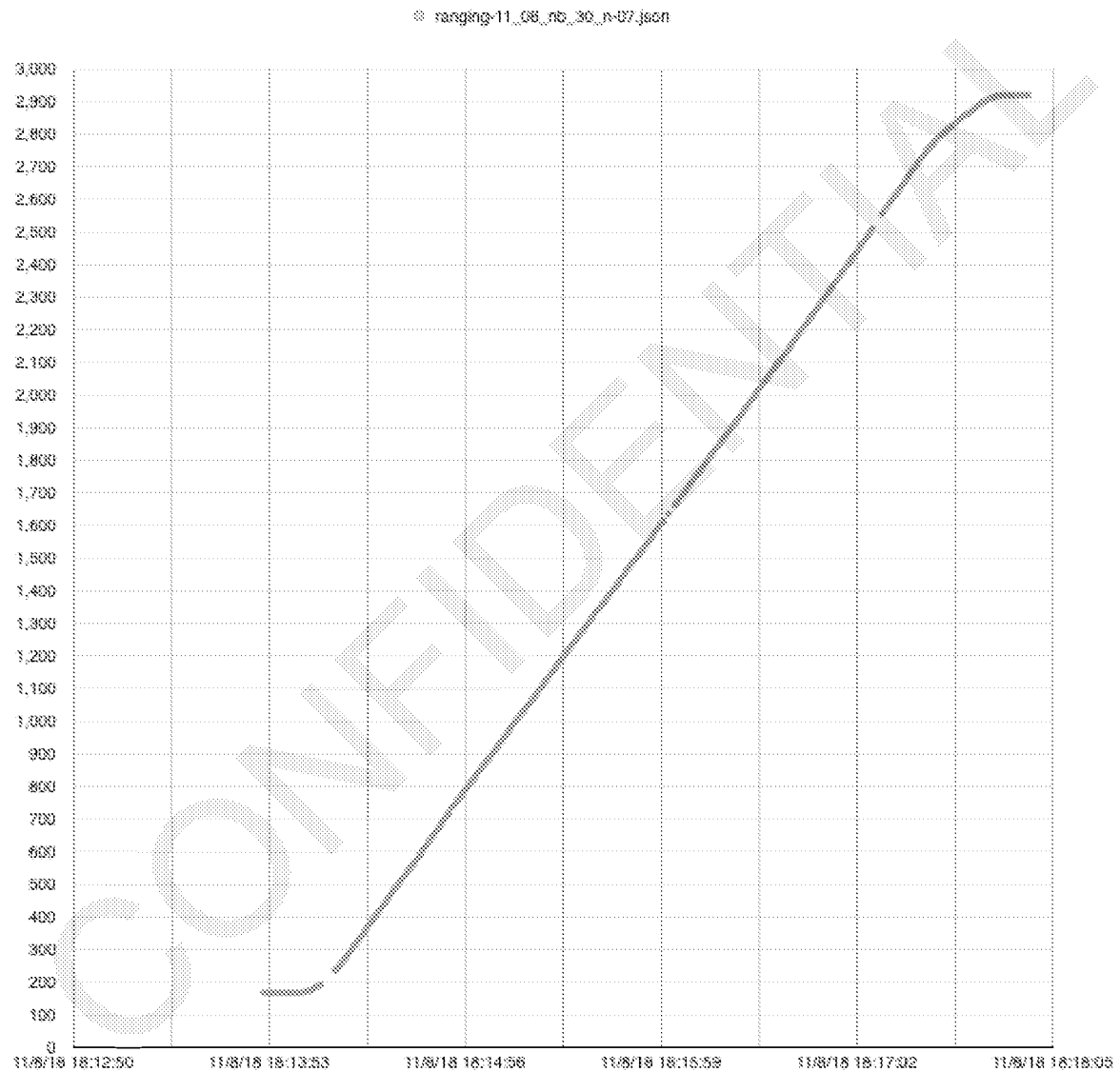
File: ranging-11_08_sb_10_s-25.json
 Description: 10mph Southbound, South Tag Controller
 Start: 08 Nov 2018 17:43:58 GMT
 End: 08 Nov 2018 17:54:44 GMT
 Location success: 1206/1221 = 98.77%

○ ranging-11_08_sb_10_s-25.json



APPENDIX "A"

File: ranging-11_08_nb_30_n-07.json
 Description: 30mph Northbound, North Tag Controller
 Start: 08 Nov 2018 18:13:51 GMT
 End: 08 Nov 2018 18:17:57 GMT
 Location success: 468/472 = 99.15%



APPENDIX "A"

File: ranging-11_08_nb_30_s-26.json
 Description: 30mph Northbound, South Tag Controller
 Start: 08 Nov 2018 18:14:16 GMT
 End: 08 Nov 2018 18:18:00 GMT
 Location success: 439/442 = 99.32%

◇ ranging-11_08_nb_30_s-26.json



APPENDIX "A"

File: ranging-11_08_sb_10_s-27.json
 Description: 10mph Southbound, South Tag Controller
 Start: 08 Nov 2018 18:22:36 GMT
 End: 08 Nov 2018 18:35:31 GMT
 Location success: 1449/1469 = 98.69%

© ranging-11_08_sb_10_s-27.json



APPENDIX "A"

File: ranging-11_08_sb_10_n-09.json

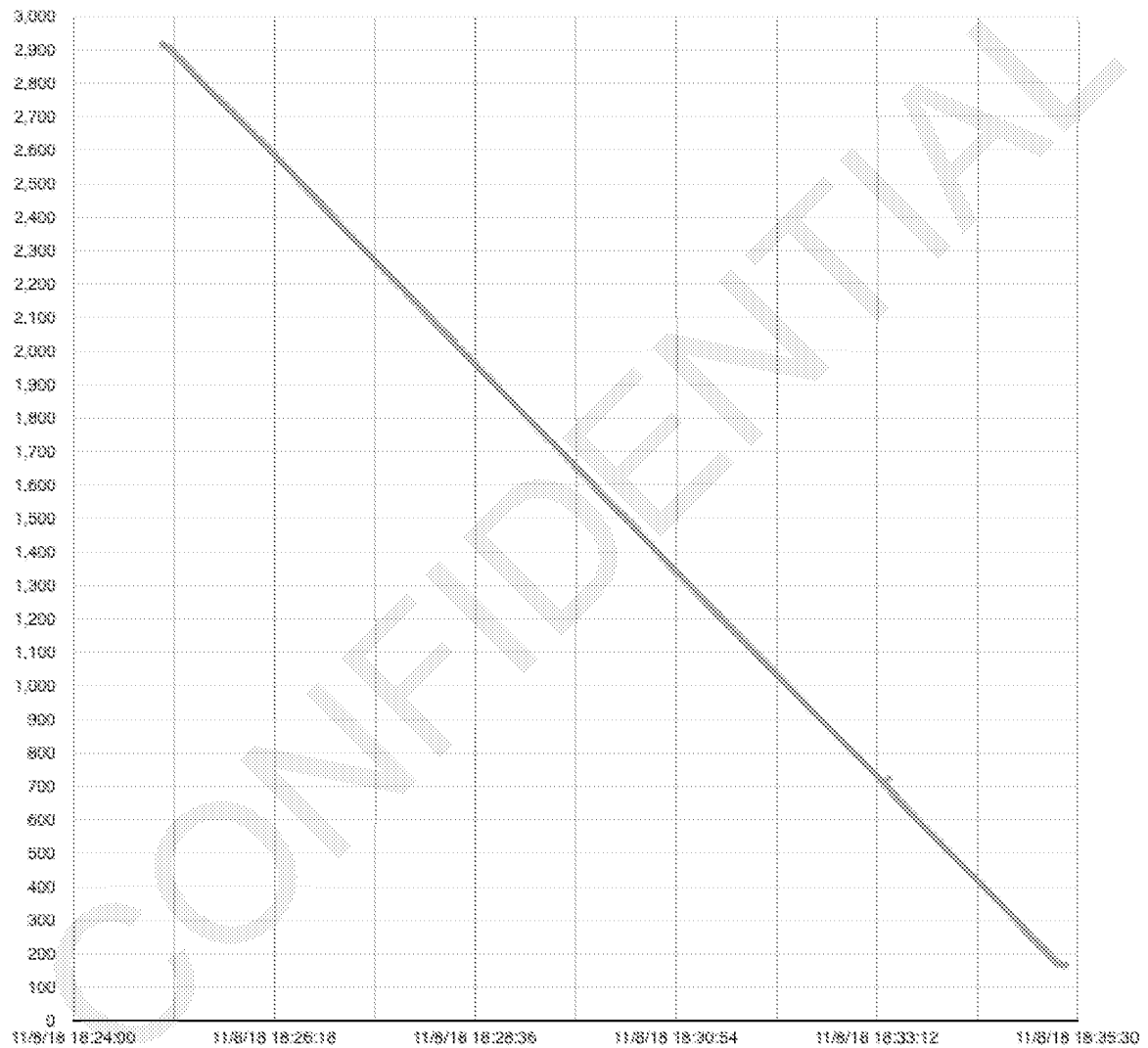
Description: 10 mph Southbound, North Tag Controller

Start: 08 Nov 2018 18:25:01 GMT

End: 08 Nov 2018 18:35:22 GMT

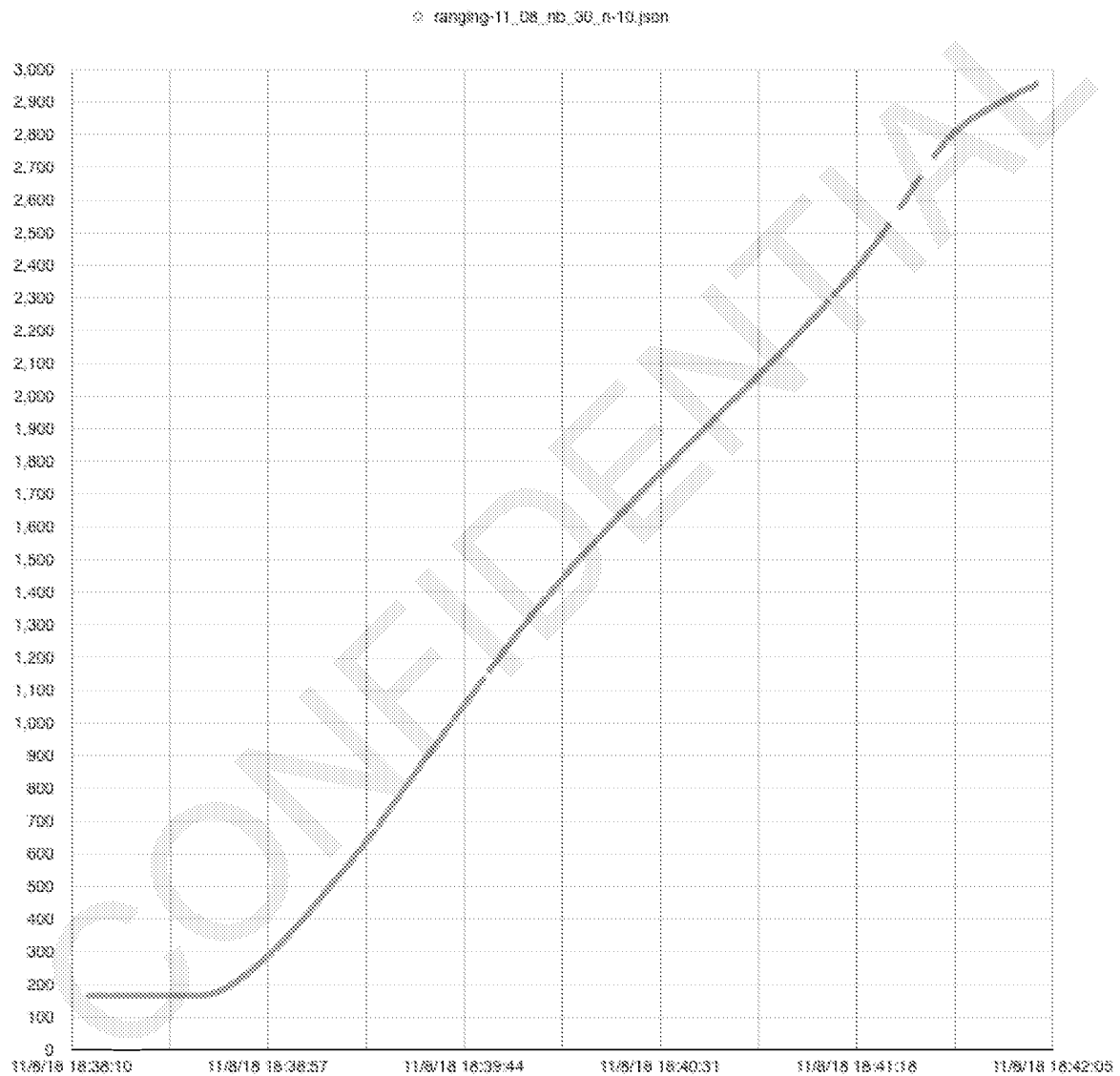
Location success: 1190/1209 = 98.42%

◇ ranging-11_08_sb_10_n-09.json



APPENDIX "A"

File: ranging-11_08_nb_30_n-10.json
 Description: 30mph Northbound, North Tag Controller
 Start: 08 Nov 2018 18:38:14 GMT
 End: 08 Nov 2018 18:42:03 GMT
 Location success: 432/441 = 97.95%



APPENDIX "A"

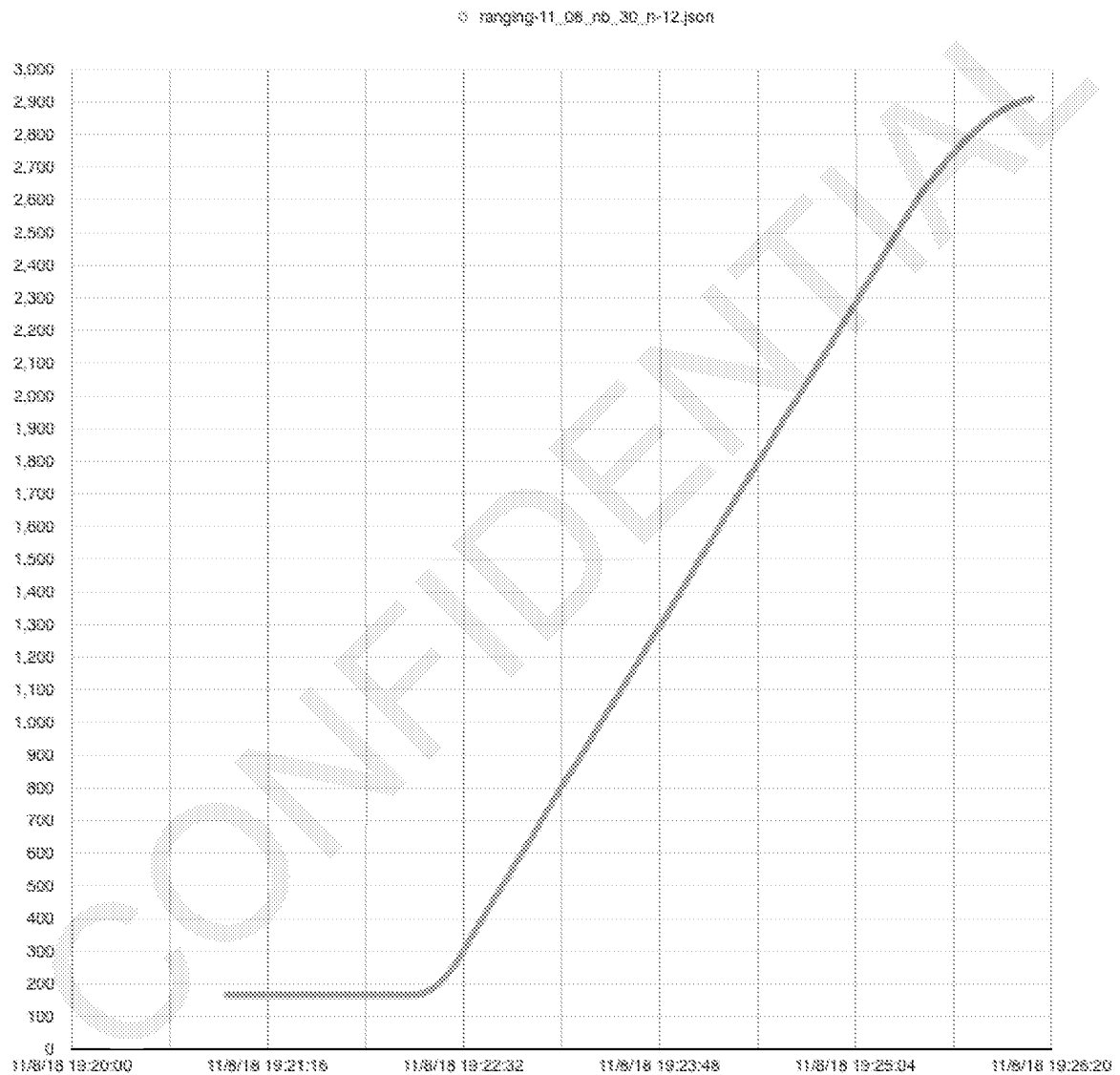
File: ranging-11_08_sb_10_n-11.json
 Description: 10mph Southbound, North Tag Controller
 Start: 08 Nov 2018 19:05:22 GMT
 End: 08 Nov 2018 19:18:09 GMT
 Location success: 1547/1570 = 98.53%

© ranging-11_08_sb_10_n-11.json



APPENDIX "A"

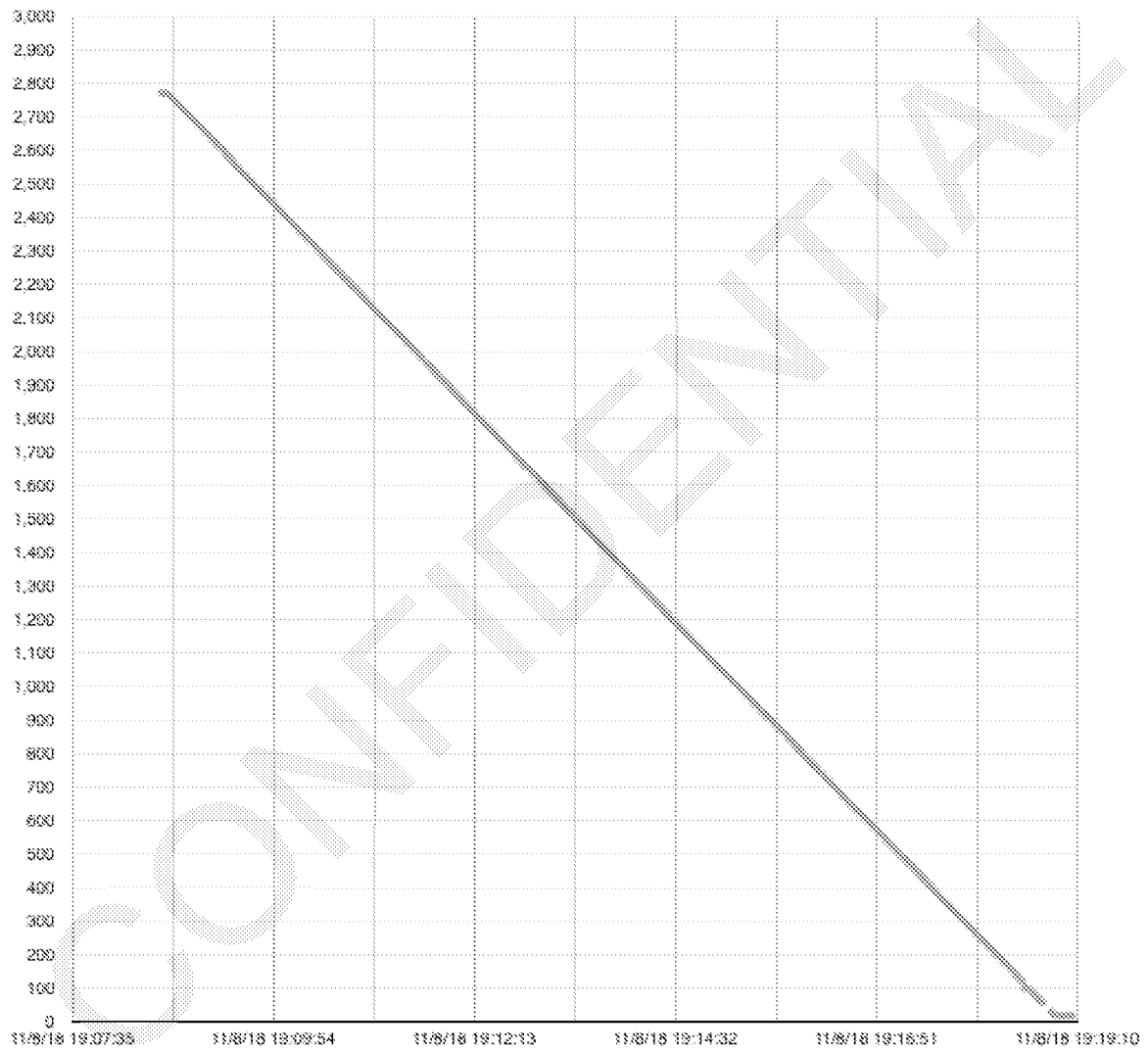
File: ranging-11_08_nb_30_n-12.json
Description: 30mph Northbound, North Tag Controller
Start: 08 Nov 2018 19:21:00 GMT
End: 08 Nov 2018 19:26:12 GMT
Location success: 616/619 = 99.51%



APPENDIX "A"

File: ranging-11_08_sb_10_s-29.json
 Description: 10mph Southbound, South Tag Controller
 Start: 08 Nov 2018 19:08:36 GMT
 End: 08 Nov 2018 19:19:06 GMT
 Location success: 1182/1201 = 98.33%

© ranging-11_08_sb_10_s-29.json



APPENDIX "A"

File: ranging-11_08_nb_30_s-30.json
 Description: 30mph Northbound, South Tag Controller
 Start: 08 Nov 2018 19:22:21 GMT
 End: 08 Nov 2018 19:26:26 GMT
 Location success: 444/452 = 98.23%

※ ranging-11_08_nb_30_s-30.json



Further Testing

Piper has identified several opportunities for improving system performance. A firmware update implemented subsequent to the testing, and witnessed by Thales and MTA, resulted in significantly improved latency and mean deviation. We encourage MTA to provide additional testing opportunities in an effort to further improve the results with the understanding that Thales onboard equipment is not necessary for us to proceed.

For instance, here are some results taken the day after the formal testing, after a full firmware update of all of the anchors and tag controller to run an experimental version of the DCS, internally referred to as "DWD". In general, the average latency is the same, however, there is marked improvement of the minimum one-way latency from around 5ms to under 3ms, and a reduction in the maximum latency. While there are some additional issues that need addressing, the overall system shows improvement and we recommend further experimentation.

Church to 7th NB ATO

Start: 11-09-2018 18:13 UTC

End: 11-09-2018 18:42 UTC

North Tag Results

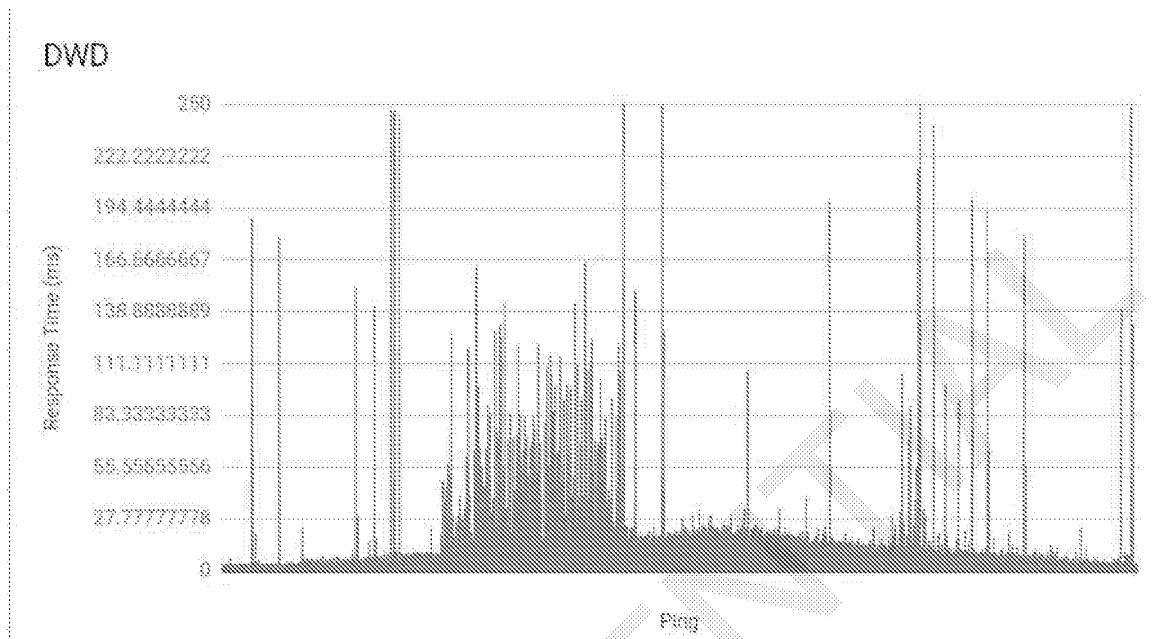
One-Way Latency: Min: 2.93ms / **Avg: 18.57ms** / Max: 281.38ms

Ping Summary:

2549 packets transmitted, 2509 received, 1% packet loss, time 639144ms

rtt min/avg/max/mdev = 5.854/37.141/562.755/51.010 ms, pipe 3

APPENDIX "A"



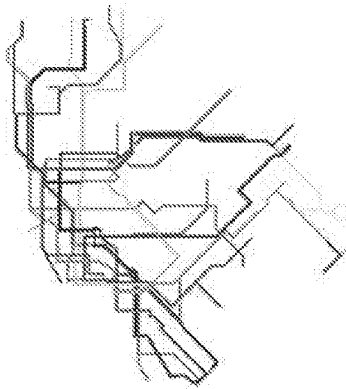
Glossary

- DCN/DCS - Data Communications Network/System
- WDS - Wireless Distribution System
- VOBC - Vehicle On-Board Computer
- ZC - Zone Controller
- UWB - Ultra-wideband
- TC - Tag Controller
- BR - Border Router
- NGPS - Next Generation Positioning System
- CBTC - Communications Based Train Control



Unsolicited Proposal
Document No.: TP-01-01

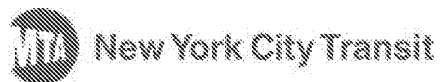
Communications Based Train Control System Enhancement Program



Rev.: 0.0.1

Date: August 22, 2019

Prepared for:



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TP-01-01 CBTC System Enhancement Program

Revision History

Revision	Date	Document Owner/Originator*	Release Description
0.0.1	08/22/2018	R. Hanczor	Initial Release

TP-01-01 CBTC System Enhancement Program



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TP-01-01 CBTC System Enhancement Program**1 EXECUTIVE SUMMARY**

This document serves as Piper Network's ("Piper's") unsolicited proposal for a Communications Based Train Control (CBTC) System Enhancement Program. The core offerings of this program are:

1. A Safety Integrity Level (SIL)-4 certified Ultra-Wideband navigation system with physical and logical interfaces to integrate with a CBTC system (also can be referred to as UWB-Based Train Control, UBTC, System);
2. UWB wayside infrastructure which has been manufactured to serve as the core to component of the UWB navigation system while also providing a wireless "mesh" Data Communications System (DCS) which exceeds the bandwidth requirements of CBTC.

This program will be supplemented with five (5) primary contract options, depending on New York City Transits (NYCTs) business needs. The options are:

1. Roadway Worker Protection (RWP)
2. Rapid Wayside Installation
3. Inter-Train Network (ITN)
4. Consist Integrity Detection System (CIDS)
5. Asset Management (AM)

The objective of this program is to lay the core foundation of the navigation subsystem for a UBTC system which can then be elevated into Revenue Service. Each of the options of this program are being presented as capabilities of UWB as a technology to enhance the CBTC system by providing added safety benefits, reducing the physical hardware needs of the system while improving reliability, or provide cost savings to NYCT in the implementation / maintenance of CBTC.

The ultimate objective of Piper is to support the overall goals of the MTA Fast Forward plan, which is to rapidly deploy an upgraded CBTC to improve transit service for New York City. To ensure successful implementation of this program, Piper will work in full cooperation and collaboration with NYCT and our partners, a key ingredient for the success and timely completion of the project. We will operate as 'one team' with full participation as necessary to support working groups and other meetings required during the project. In the spirit of the 'one team' approach, Piper Networks intends to employ a local Program Management team with expertise in Train Control Systems / Safety Systems and delivery of complex programs.

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2 IMPLEMENTATION

2.1 Deployment Area

Piper is presenting three (3) options for the deployment area, however, Piper will ultimately support whichever approach (even if not listed below) that aligns with NYCT's implementation strategy and business needs. The three (3) options are:

1. Deployment on the Queens Boulevard Line (QBL), between the limits of Grand Avenue – Newtown Station and Forest Hills – 71st Avenue (≈2 miles).
2. Deployment on the Eighth Avenue Line, between the limits of 207th Street Station and 168th Street Station (≈2.1 miles).
3. Deployment on the A-Division, on the Lexington Line between the limits of 59th Street – Lexington Avenue Station and 14th Street – Union Square Station (≈2.3 miles).

Each approach has its benefits, which are further detailed below.

2.1.1 Queens Boulevard Line (QBL)

The Queens Boulevard Line, abbreviated as QBL, is a line of the B Division of the New York City Subway in Manhattan and Queens, New York City, United States. The line, which is underground throughout its entire route, contains 23 stations and is served by four (4) overlapping routes, the E train, the F train, the M train, and the R train. The areas selected on the QBL are advantages as the QBL line is currently in the process of being retrofitted with CBTC, which the proposed system could integrate into. Additionally, the diversity of train routes / train types allows for Piper to demonstrate the robustness of the UWB positioning system.

2.1.2 Eighth Avenue

The Eighth Avenue Line is a rapid transit line in New York City, United States, and is part of the B Division of the New York City Subway. The line runs from 207th Street in Inwood south to an interlocking south of High Street in Brooklyn Heights, including large sections under St. Nicholas Avenue, Central Park West, and Eighth Avenue. The entire length is underground, though the 207th Street Yard, which branches off near the north end, is on the surface. The whole line is served at all times by the A train, which runs express except during late nights. Similar to the above, the line is currently in the process of being retrofitted with CBTC, which the proposed system could integrate into.

2.1.3 A-Division, Lexington Line

The Lexington Avenue Line is one of the lines of the A Division of the New York City Subway, stretching from Lower Manhattan north to 125th Street in East Harlem. The line is served by the 4, 5, and 6 trains. The A-Division provides a very advantages opportunity for UWB to be installed, for the simple reason that CBTC work has not begun on the A-Division so no current CBTC work would be affected by the UWB construction, and the A-Division lines and vehicles do not interoperate with B-Division so it is the perfect division for which a non-I2S CBTC system could be implemented. For this implementation the Lexington Line is proposed, in which Piper will demonstrate the ability to accurately track the vehicles location as they traverse the project limits, the ability for the system to provide a high-bandwidth wireless mesh DCS underground, and demonstrate the accurate reporting of the assets to the RTO.

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2.2 Architecture

The Piper train positioning (detection system) is based on redundant mobile radio units (train-borne) determining position by geographic cross referencing of three or more fixed line-side wide frequency band radio beacons.

To reach the required safety integrity level (SIL4 requirement) for the single main safety function of train localization, the system shall be based on composite fail safe architecture.

The current spacing of the anchors along the wayside is primarily determined by the ambient RF conditions in the area, the frequencies selected by Piper to ensure optimal communication between UWB devices, and the track geometry - taking curve, grade, and elevation into consideration. In the 2019 UBTC Pilot Program, Piper deployed anchors at 250-300' spacing on average. During the shadow mode data collection process, Piper will review the ranging data collected and perform simulations to determine the necessary spacing in a revenue system in order to achieve complete communication coverage in the event of failed wayside units. It is anticipated that significantly less anchor density will be required to meet the safety requirements.

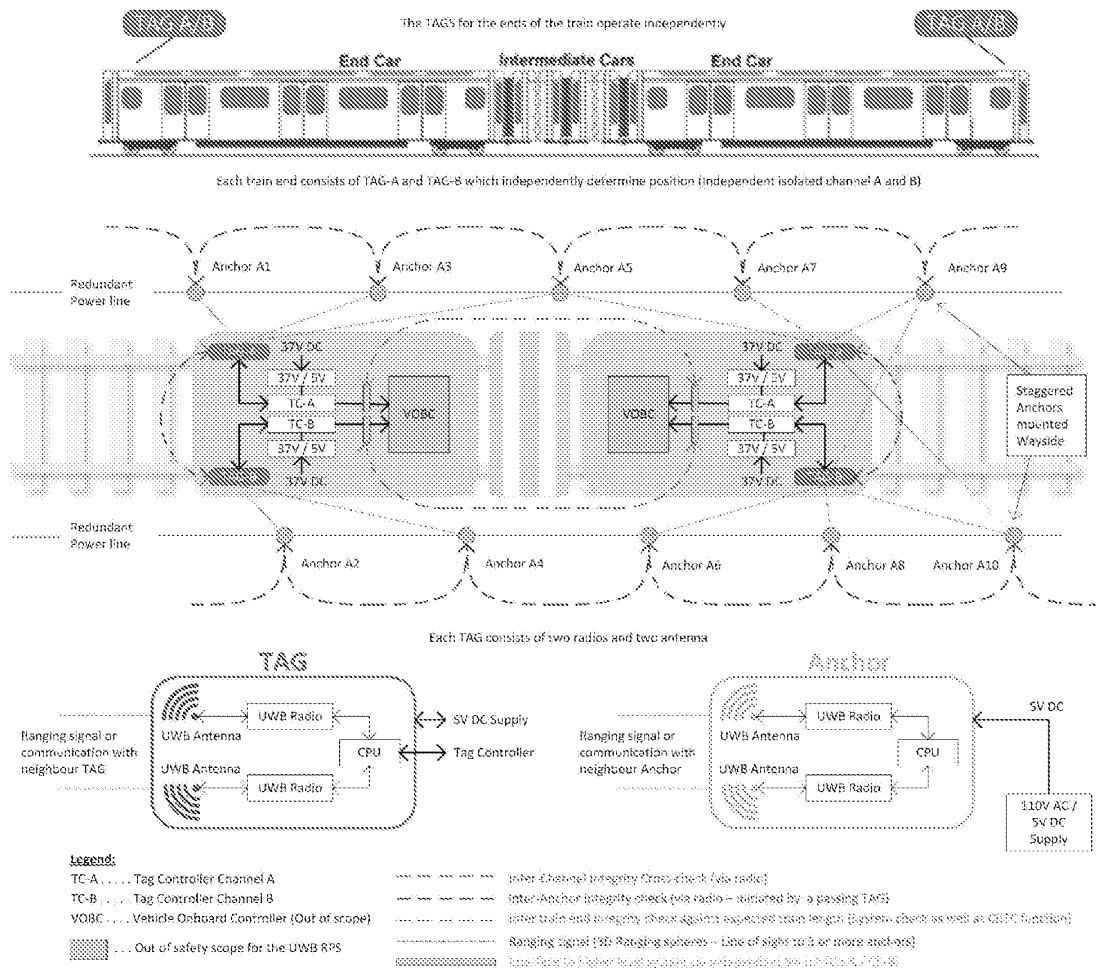


Figure 1 Top Level Schematic Block Diagram

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2.3 Core System Functions

The core systems functions being demonstrated are a SIL-4 certified navigation system which is interface ready with CBTC, and a wireless DCS mesh network, these core functions and core infrastructure are prerequisites to enabling the options listed in this document. This section provides the benefits that these functions can provide to NYCT.

2.3.1 Positioning

Piper Networks is developing a SIL-4 compliant UWB Individual Sub-System for Train Positioning. System Identifier: ETLS-1003.3. For all system, hardware and software development processes, Piper adheres to all the required safety processes and design requirements in accordance to the CENELEC EN50129 [101], EN50128 [102] and EN50159 [103] standards. Piper has invested in the necessary compliance consulting to ensure that a safety certifiable UWB Train Positioning System can be delivered to NYCT, making NYCT the only agency to employ a SIL-4 UWB positioning system. To this end, a SIL-4 certified positioning system is the foundation for which Piper intends to build upon to provide additional features (e.g. RWP, CIDS, etc.) and with a great level of confidence that these additional system features will satisfy NYCT's safety requirements for implementation into revenue service.

2.3.2 Data Communications System (DCS)

Installing the Piper DCS system has many advantages for NYCT. For starters, the Piper DCS will not require any additional infrastructure on the wayside, as the Piper Anchor will be dual equipped with UWB radios for positioning and DCS radios for DCS. This enables NYCT to get more benefits for a work effort that would have already been planned. Additionally, Piper proposes a wireless mesh network which exceeds that data bandwidth requirements of CBTC, as demonstrated in the MTAIT POC2 program, and is expandable by way of Fiber to be able to provide "Passenger Wi-Fi" or generate additional revenue by way of ad streaming.

It is important to distinguish the differences between the wireless mesh network and the network supported by Fiber, as well as identify the implementation advantages that this provides to NYCT. Piper's DCS network without any Fiber can be installed rapidly and fully support the CBTC data bandwidth needs. This provides a significant advantage to NYCT as to enable NYCT to rapidly "turn on" sections of track without the need of running miles of Fiber as currently required. After the wireless mesh network is activated to support the Train Control System, NYCT can then return at a convenient time to begin laying down Fiber with minimal impact to the public as the Fiber will not be driving anything on the critical path for Train Control. With this in mind, once the Fiber is available, the additional features (e.g. Passenger Wi-Fi or Ad Streaming) can be enabled.

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**2.4 System Function Options**

The following describes the business case to be made for each of the optional features of the program.

2.4.1 Roadway Worker Protection (RWP)

Piper's Roadway Worker Protection system is specifically engineered to enhance the safety of the roadway workers by enabling train crews (and the Train Control System) to be aware of roadway workers on their route. The Piper RWP system will enable the Train Control System to take safety measures, such as Emergency Brake, when the operating train encroaches too closely to a work zone without authorization or acknowledgement from the Roadway Workers. This system could be leveraged as a means to reduce workplace injuries and streamline the NYCT process for doing work on the wayside. For example, if a safety system is provided to the roadway workers and is integrated into the train control system, NYCT can reduce the amount of flaggers required for work without a G.O. and in turn improving on work efficiency.

2.4.2 Rapid Wayside Installation

If this option is selected, Piper will employ Snake Tray as a subcontractor to develop rapid installation kits for the UWB anchors. Snake Train will provide a flexible consolidation point in the deployment structures, plenum-rated with fire-rated foam sealing kits, and simplify installation / changes to the wayside infrastructure. Piper will work with Snake Tray to design brackets which are compliant with NYCT specs and demonstrate that the Anchors can be installed with minimal service interruptions.

2.4.3 Inter-Train Network (ITN)

One area of significant expense to NYCT is the procurement and installation of Inter-Train Networks. Piper proposes the use of the inactive tags and tag controllers installed on UWB equipped trains as a method for achieving wireless unit-to-unit networking

2.4.4 Consist Integrity Detection System (CIDS)

NYCT currently employs a couple of different methods as an Auxiliary Wayside System (AWS). An AWS is a back-up or secondary train control system, capable of providing full or partial automatic train protection for trains not equipped with trainborne CBTC equipment, and/or trains with partially or totally inoperative trainborne CBTC equipment. The Auxiliary Wayside System employed by NYCT currently is traditional track circuits and axle counters. One issue with these AWS systems is they are expensive to install and expensive to maintain.

Piper is proposing to demonstrate a Consist Integrity Detection System (CIDS) which can be introduced into the NYCT system at a lower cost than axle counters, will have capabilities of reporting their own status to an RCC to enhance maintenance abilities, be able to share the data collected with the CBTC systems for consist integrity checks, and be capable of mechanically shunting the signal system. The synergy between the CBTC intelligence and the CIDS output data can be put to profit in various ways: e.g. train movement detection between two occupied track zones, integrity check of train length and determination of the direction of travel by an independent intelligent radio network. More details on the design of CIDS is described in Section 3.

2.4.5 Asset Management (AM)

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The Piper Asset Management system can be seamlessly integrated into NYCT's Rail Control Center (RCC), either as a standalone application or as an input to NYCT's existing AM system if applicable. The NYCT operations team can leverage the Piper AM system to record and track the location of UWB assets that are considered critical in the safe operation of rail operations. These assets include, but are not limited to, UWB Anchors, UWB Tag Controllers, and UWB RWP devices. Alternatively, Piper can consume the health status of external devices to provide NYCT's RCC with one central monitor with a holistic view of the entire network.

All assets report a configurable amount of health statuses enabling NYCT's operations team to conduct trend analysis, react quickly to malfunctioning devices, and determine a preventive maintenance schedule. While the decision to NOT enable this interface to the RCC does not affect the safety functions of the system, enabling the Piper AM system can improve the system reliability and NYCT's operational effectiveness.

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3 SYSTEM FUNCTIONS – TECHNICAL DESCRIPTION

3.1 Core Function – Positioning

The Piper train positioning (detection system) is based on redundant mobile radio units (train-borne) determining position by geographic cross referencing of three or more fixed line-side wide frequency band radio beacons.

To reach the required safety integrity level (SIL4 requirement) for the single main safety function of train localization, the system shall be based on composite fail safe architecture.

The interaction between Piper Anchors mounted high on the walls of the tunnel and Piper Tags installed on the train facilitates the geolocation of a given train. As the train moves through the tunnel, distance is measured between Anchors and Tags using a calculation based on the Time-of-Arrival of a radio pulse. The Tag Controllers use the ranging data, the known positions of the anchors, and a mathematical model of the track to compute the train's location. The Piper Tag Controller then produces a UDP packet defined by a OBCU and injects into the Thales trainborne network.

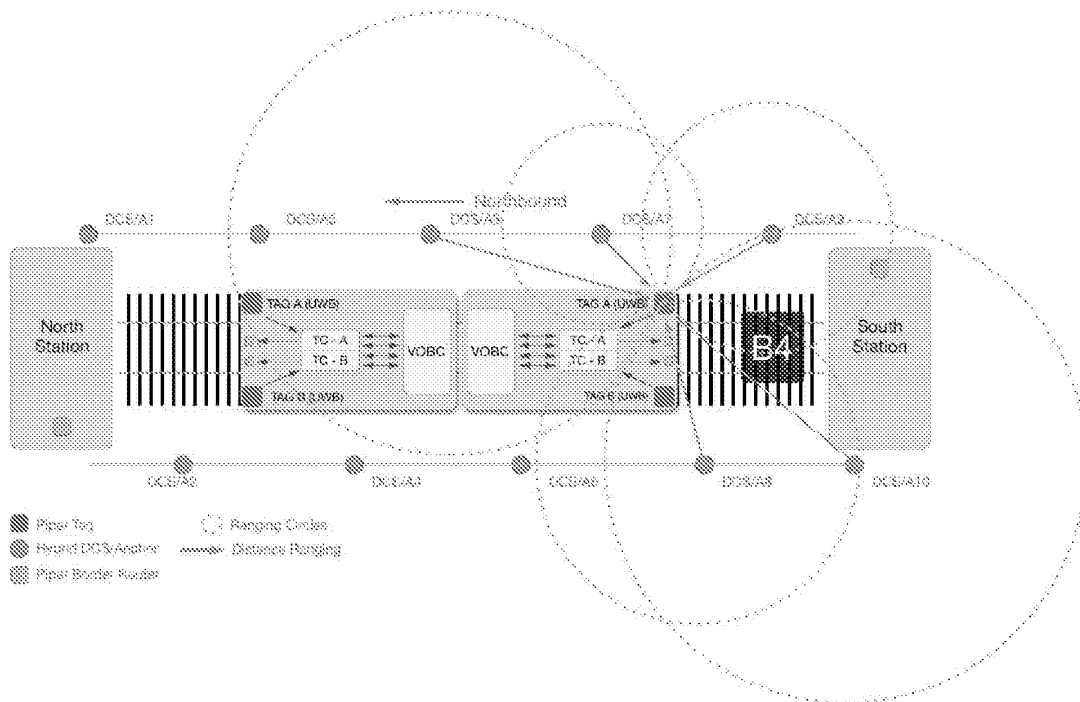


Figure 2 High Level Positioning Architecture

Please note the dual channel architecture showing full independence between the processing units and the final stage combination providing the train positioning information to the higher-level system.

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3.2 Core Function – Data Communications System (DCS)

The Piper Data Communications Network consists of three main components:

- On/off-ramp of data
- A redundant WDS network
- Border routers to connect with Zone Controllers or wayside networks

NOTE: The descriptions and illustrations provided in this section are based on Piper's deployment of a WDS network during a proof of concept program on the Culver Test Track in 2018.

The Piper Tag and Piper Anchors provide the on/off-ramp (to and from the train) using the UWB radios. The Piper Tag sends data over UWB to the Piper Anchors (on-ramp). These data are then forwarded to the Piper Data Communications Network which is a Wireless Distribution System (WDS) formed by the two 5GHz radios on the Piper Anchor. One 5GHz radio is used to send data north, the other 5GHz radio is used to send data south. This provides a full-duplex solution mitigating per hop bandwidth degradation. Any data received by a 5GHz radio is forwarded to the UWB radio and sent to the Piper Tag (off-ramp) as dictated by the routing tables.

The Piper Border Router receives data from the Piper Anchors and forwards those data to the EMD Switch. The Piper Border Router also routes data received by the EMD Switch to the Piper Data Communications Network.

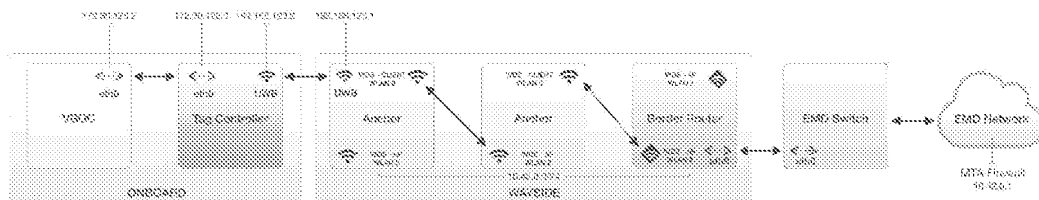


Figure 3 Example Communications Stream via Piper DCS

The Piper Anchors transmit beacons periodically, typically 3-10 times per second. These beacons contain the tunnel location of the anchor (relative distance to the "origin") along with additional information used to form the Piper WDS. Piper Anchors use this beacon data and the RSSI from the received beacon to create routes from the anchor to the Piper Border Router. A proprietary routing algorithm minimizes latency and increases communication efficiency.

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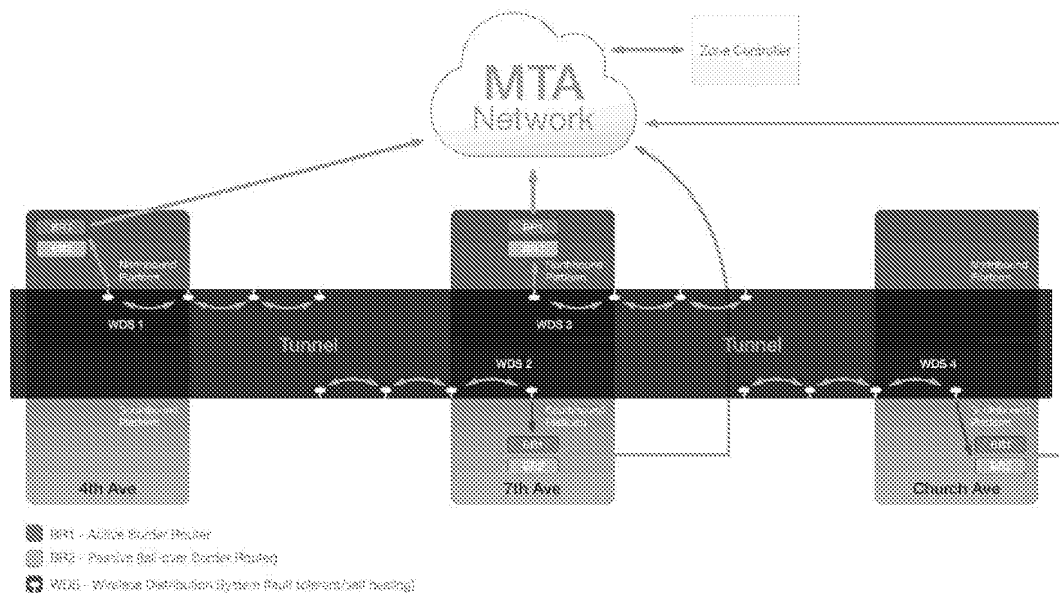



Figure 4 Piper Network Configuration Supporting Multiple Channel Streams

Fault Tolerance

The Piper Data Communication Network is designed such that any single Piper Anchor failure will not affect overall throughput or latency. The Piper Anchors are constantly sending and receiving beacons and heartbeat messages. The beacon data is sent from the Piper Border Routers out to the Piper Anchors that contain no children (the leaves). Likewise, leaf Piper Anchors originate heartbeat messages sent to the Piper Border Router. So, there is health data sent in both directions. The Piper Anchors and Piper Border Routers use these data (or lack thereof) to determine the health of adjacent anchors. If a certain number of heartbeats or beacons are missed, surrounding anchors will consider the failing anchor down and route around the anchor. Once the anchor is back on-line, routing to that anchor will resume.

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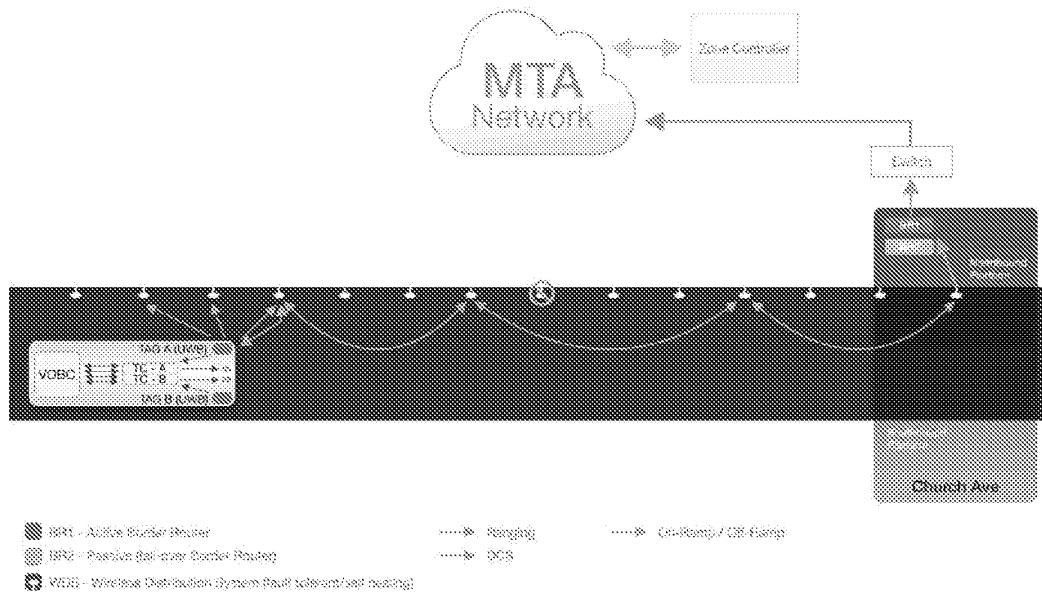



Figure 5 Piper Routing w/Failed Anchor

3.3 Optional Feature – Roadway Worker Protection (RWP)

Piper has successfully demonstrated the use of wearable devices to determine accurate position of track workers. These devices are designed to alert both track workers and train operators to hazardous proximity events. Wearable devices equipped with UWB radios connect with the wayside anchors and DCS network to determine position on or near a live track. Through continuous detection of worker positions and train positions, Piper calculates the distance between workers and trains and send alerts in real time based on safe separation rules. Unlike peer-to-peer systems that perform distance ranging only when radios on workers and trains have line-of-sight connectivity, Piper has developed a system that utilizes the wayside UWB network to simultaneously monitor the two positions, trigger alerts, and integrate with the onboard EB controller to stop the train in the event of unheeded warnings.

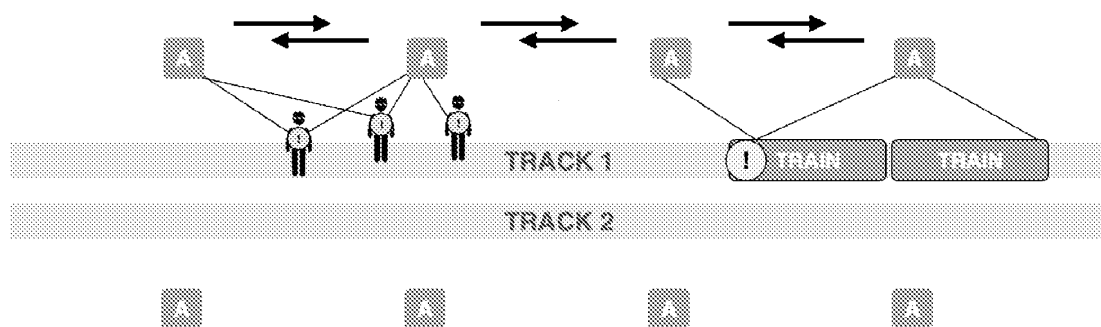


Figure 6 Piper Roadway Worker Protection Architecture

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Piper has developed two iterations of its UWB wearable track worker safety device. Both are rechargeable with a battery life of more than 24 hours in full duty cycle. Additionally, Piper has developed a track worker vest that is equipped with super bright LEDs that become activated during the alerting process. The devices use a shared PCB platform and are expandable to accommodate NYCT's specific functional requests.

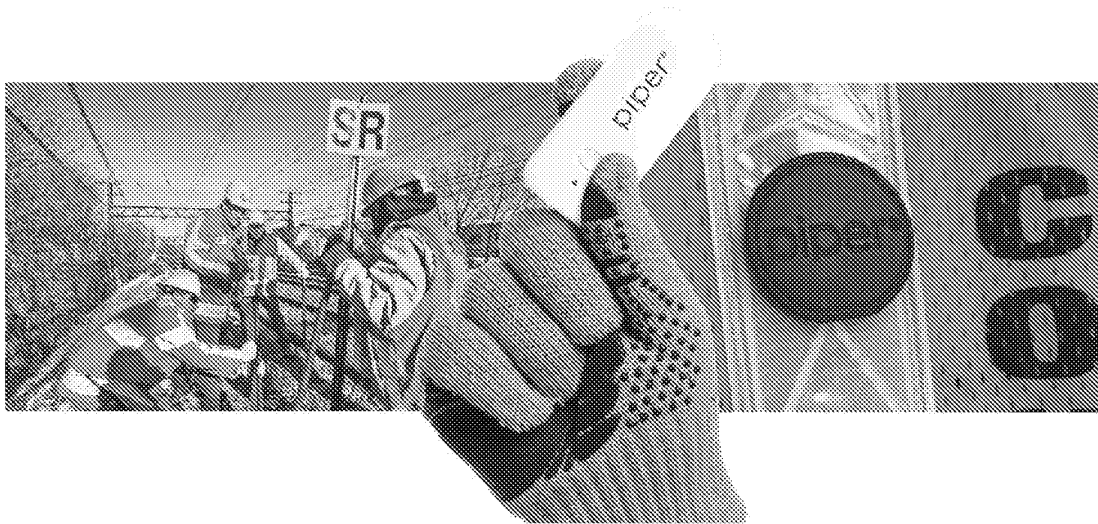


Figure 7 Piper Roadway Worker Protection

3.4 Optional Feature – Rapid Wayside Installation

Snake Tray is proposed as a subcontractor for this scope of work. Snake Tray would work with Piper and NYCT to develop a bracket design which complies with NYCT standards and enables rapid wayside installation of the Piper Anchors and a power supply that also serves as a fiber network switch. An example of a potential design is shown below.

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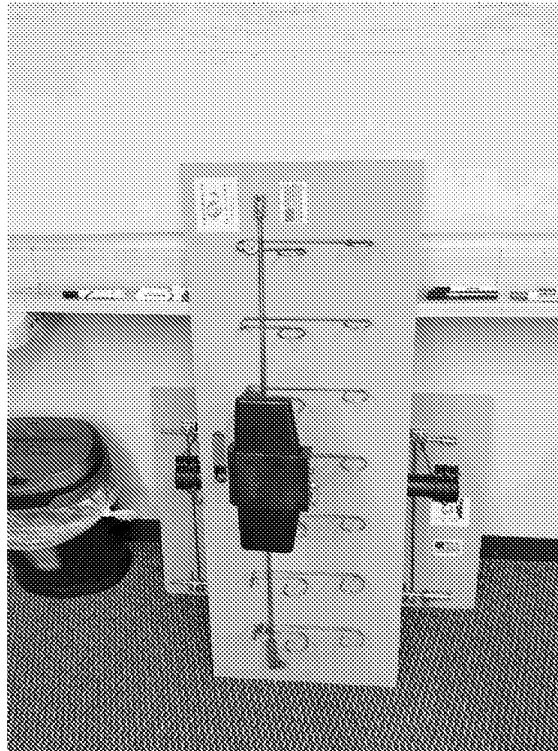


Figure 8 Snake Tray Example

Greater mechanical information will be provided by way of a design which is sealed by a Professional Engineer, however, Piper would need to know the selected deployment line is to design a custom bracket for the territory. Piper can begin working with Snake Tray immediately to design the tines necessary for accommodating wayside equipment.

3.5 Optional Feature – Inter-Train Network (ITN)

Piper takes advantage of the ITN as a way to network the tag controllers on the coupled units, compare ranging and positioning information, and provide the OBCU with reliable location data. In a typical configuration, there are 4 tag controllers installed per unit, and 8 per coupled train. In the diagram below, the active units (green) are located at the ends of the coupled trains. The inactive units (blue) can be repurposed to handle the telemetry data networking required by CBTC and deliver a fully connected train. The abundant bandwidth achieved on the UWB network, combined with redundant, multi-directional networking capabilities make this solution a viable alternative to conventional and expensive ITN systems.

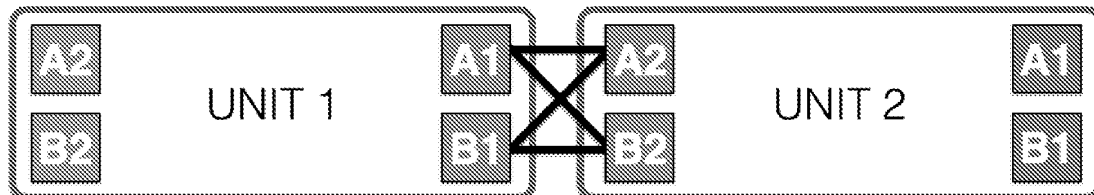


Figure 9 ITN Architecture

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3.6 Optional Feature – Consist Integrity Detection System (CIDS)

Piper's Consist Integrity Detection System offers a cost-effective alternative to CBTC integrated axle counters. Through the installation of inexpensive and easy-to-deploy and maintain "Car Counters", the Piper CIDS provides NYCT with a viable alternative to axle counters or as a safety overlay of non-CBTC track circuits.

The system works by counting the UWB radios on the trains, each with a unique identifier recognized by the network. In the event the counter misses an anticipated car, potentially indicating a compromised consist, it connects simultaneously with the Zone Controller (in CBTC systems) and a Piper controlled Circuit Shunt to dynamically trip a signal alerting approaching trains of the hazard.

The system can also communicate the position of non-revenue trains to the CBTC system and the AWS system.

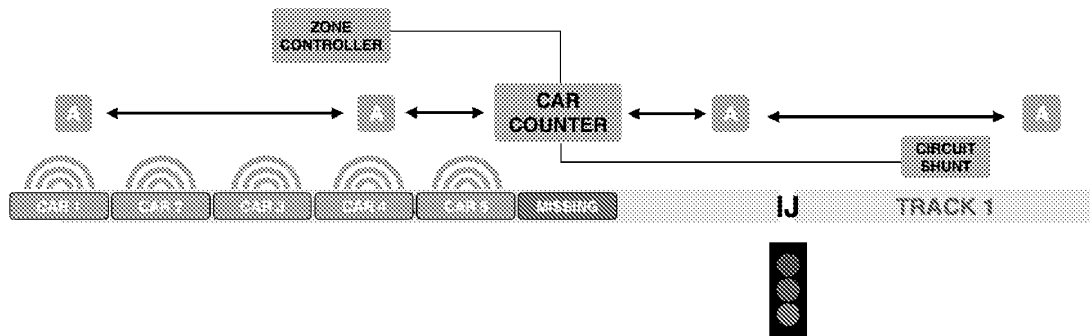


Figure 10 Consist Integrity Detection System

3.7 Optional Feature – Asset Management (AM)

The Piper Asset Management system provides three (3) feature sets, described below:

1. Remote Monitoring

- Periodic Monitoring - Piper's AM system will periodically send asset messages and trending data.
- Detected Conditions - Piper's AM will alert on specified asset changes or out-of-normal conditions. Examples, high radio temperature, firmware version change, etc.
- On-Demand Monitoring - Piper's AM will perform specific monitoring actions on demand. Examples - Query current configuration parameters
- Monitoring Management - Piper's AM system can provide remote management functions. These can include modifying configuration parameters, or performing corrective action.

2. Remote Software Deployment

Piper provides remote deployment functionality allowing users to stage, verify, install, modify, roll back, and uninstall packages remotely with complex rules and condition checks.

3. Remote Readiness Checks

Piper's AM system can check and return asset information and status for onboard subsystems. Piper can work with NYCT to design a scoring system (for example, Pass/Fail; or rate a unit from 1-10) to assess the current state of the onboard Train Control System, and compare the relative readiness of the units.

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4 PROJECT EXECUTION

4.1 Org Chart

Piper Networks intends to employ a Program Management team with expertise in Train Control Systems / Safety Systems and delivery of complex programs for NYCT. Key personnel of the program management team will be locally based to support the implementation and provide a consistent customer interface to NYCT. The proposed org chart is listed below, names and resumes will be provided to NYCT separately if NYCT acknowledges interest in the proposed program.

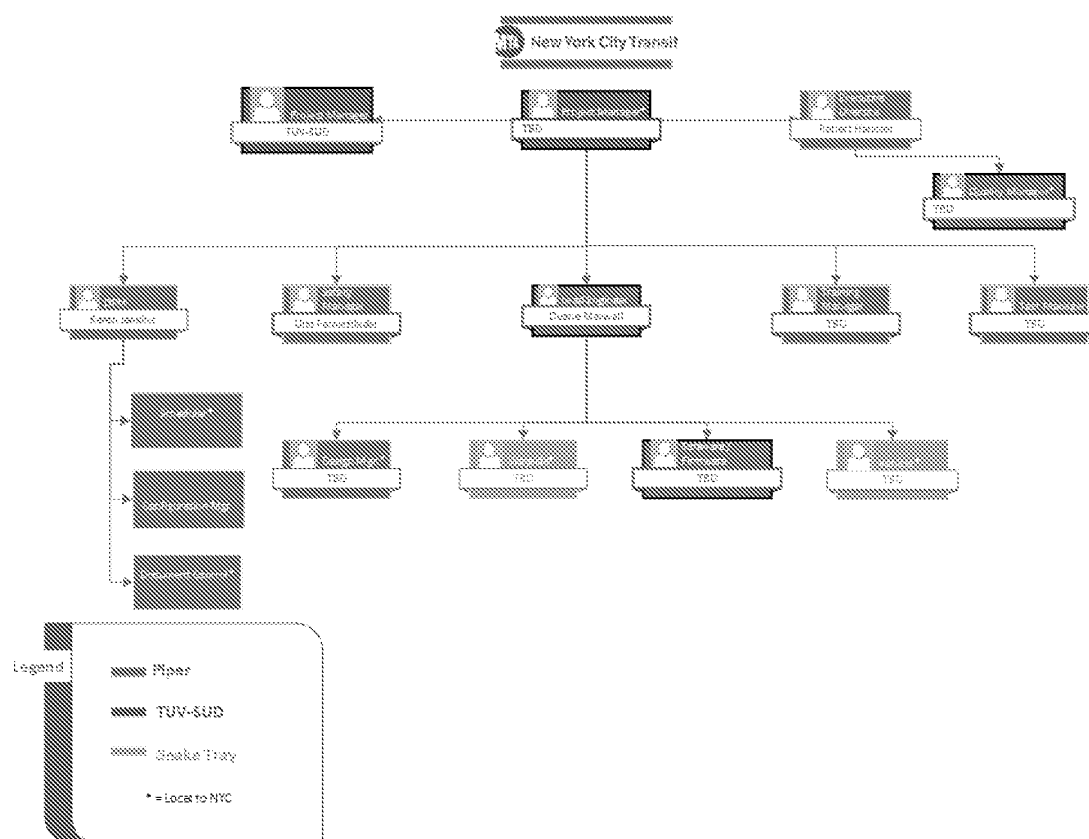


Figure 11 Piper Project Org Chart

4.2 Safety Program

Piper is developing a safety compliant UWB Sub-System for Train Positioning.

For all system, hardware and software development processes, Piper shall adhere to all the required safety processes and design requirements in accordance with the CENELEC EN50129 [101], EN50128 [102] and EN50159 [103] standards (plus any referenced standards).

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Piper's Safety Program outlines the safety assurance tasks applied during the development of the above described system. The methodology for safety verification follows a proven structure that identifies and then analyses all safety-related functions performed by the product. The validation will show, through inspection, test, demonstration or analysis, that the fundamental requirements for product safety are implemented in the design.

The Safety Program defines the planning, implementation, monitoring and control necessary for ensuring the safety of the system. It also defines the tasks necessary for identifying, tracking, evaluating, and eliminating or controlling hazards and unsafe failures. The specific objectives of the safety program are summarized below:

- Develop, implement, and document the goals, conventions, and practices of the safety program in a verifiable manner.
- Identify and evaluate all hazards and eliminate, control, or minimize these hazards to an acceptable level.
- Perform qualitative and quantitative analyses demonstrating that the design satisfies the stated criteria, requirements, and product safety targets.
- Establish Verification and Validation processes for all safety-related design elements, and document the **V&V** activities as performed.
- Establish testing requirements for the safety-related product elements, and show that product safety is adequately verified by inspection, test, demonstration or analysis.
- Support safety approval of the products

4.3 Survey

Piper will perform a comprehensive RF site survey, which will be done in several phases. The objective is to actually measure the frequency, signal strength, and modulation characteristics of the existing RF activity along the entire deployment area. This scan will be limited to the frequency bands of interest for use in the chosen implementation, as well as to lower frequency usage which might also occupy the frequency bands of interest as a result of harmonics.

We will perform this survey in several passes along the Right-of-Way (ROW) over the identified deployment area. The survey phases will include the following:

1. Measurement during normal peak revenue hours on a suitable open vehicle. (Measurement must be performed during normal workday hours in order to get an accurate idea of the frequencies in use during peak times). The vehicle can be moved at the normal service pace while the initial presence scan is accomplished. We will note locations of particular interest and we will visit these locations on foot, as needed, for additional scan studies.
2. Measurement in and around each type of vehicle during normal vehicle operation. This measurement may be done along the vehicle test track.
3. Measurement at each station along the deployment area during daytime operations.
4. Extended measurement at locations of interest that were identified during earlier surveys.

The data captured in this RF site survey will be studied to determine if action is necessary to avoid interference with the Piper UWB system operation or to avoid interference caused by the Piper UWB system.

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4.4 Verification and Validation (V&V)

Piper will dedicate a team for the development of this project. The team is composed of core team members and external independent consultants which will perform the V&V tasks, as illustrated below.



Figure 12 V&V Responsibility Structure

Piper defines Verification and Validation (V&V) as the following:

Validation: The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements. The process of providing evidence that the software and its associated products satisfy system requirements allocated to software at the end of each life cycle activity, solve the right problem (e.g., correctly model physical laws, implement business rules, use the proper system assumptions), and satisfy intended use and user needs.

Verification: The process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase. The process of providing objective evidence that the software and its associated products conform to requirements (e.g., for correctness, completeness, consistency, accuracy) for all life cycle activities during each life cycle process (acquisition, supply, development, operation, and maintenance); satisfy standards, practices, and conventions during life cycle processes; and successfully complete each life cycle activity and satisfy all the criteria for initiating succeeding life cycle activities (e.g., building the software correctly).

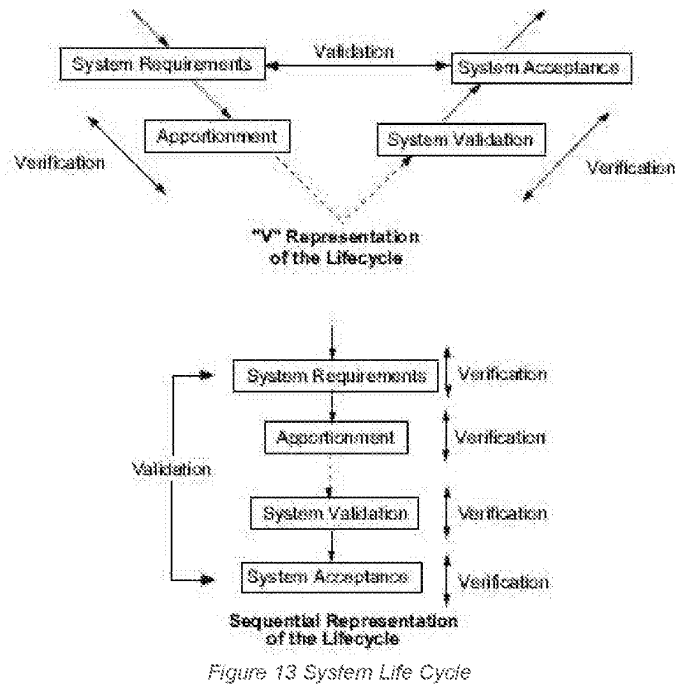


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Testable vs Non-Testable Requirements:

- Testable requirements are functional requirements that have a specific action or output.
- Non-Testable requirements are non-functional. Non-Testable requirements will be verified and validated via analysis, inspection, submittal, or audit.

The following diagram (extracted from the relevant standards) identifies the verification task and highlights the differences between the verification and validation activities.



Piper has developed a V&V plan which is utilized to bridge Project and subcontractor software V&V activities along with guiding the software integration and software V&V tasks. All aspects of the software V&V will be monitored at the overall project level. The Piper V&V plan will be delivered as a part of this proposed program and will apply to all V&V activities being performed for the project, including integration, demonstration, inspection, and testing of the system and subsystems.

Piper's V&V plan conforms to the following standards:

1. IEEE STD 1012 - IEEE Standard for Software Verification and Validation
2. IEEE STD 1012a - Supplement to IEEE Standard for Software Verification and Validation

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**4.5 Interface Management**

Ensuring all levels of integration between systems and subsystems begins during the Project Design Phase where Interface Control Documents (ICDs) are developed to track and manage interface points. Critical interfaces may create derived requirements that must be incorporated into subsystem designs and plans. The ICDs are an effective way to actively track Open Interfaces, and to provide clean documented records of all Closed Interfaces. The key ICD deliverable to NYCT will be the UWB to OBCU ICD, which Piper is offering to work with NYCT, it's consultants, and the CBTC suppliers to develop an agreed interoperable ICD which can be inherited into the Interoperable Interface Specification (I2S). Other ICDs that Piper will generate will be specific to the optional parts of this proposal, such as RWP and CIDS.

Piper will work with all team members to establish regular periodic integration meetings using ICDs to establish the matrix of Project ICDs during the Design Phase. During the Project Construction Phase, ICDs continue to be tracked and are often modified due to Field Change Requests. A project change-control process will be in place to address any modification in ICDs including, if necessary, adjustment or clarification to the final derived requirements. The ICDs are subsequently monitored into the Project Testing Phase. The interfaces then become paramount in the commissioning of the entire system. The ICD is included to fully document the testing needs of the interface. Interfaces form the basis for integrated testing, which is a prerequisite for Final System Safety Certification.

4.6 CDRLs

List all CDRLs will be provided in the final proposal.

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