Location Engine
for Co-operative Positioning

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Introduction

In WP001 we introduced the concept of relative positioning using collaborative techniques as used in the Series 500 Cluster location system.

In a Series 500 wireless mesh sensor network, devices (nodes) broadcast radio signals (referred to as chirps) to neighbours within radio range. By measuring the precise Time of Arrival (ToA) of chirps received a node is able, with the help of the data included in the chirp, to compute its position relative to its neighbours. Whilst we refer to ToA (Time of Arrival) it is more usually known as OTDOA (Observed Time Difference of Arrival).

Computation of positions may be carried out by the node itself, or it can transmit measurements to a separate position processor.

In its most general form every node listens to every other and uses this information to compute its own position.

In this paper we present a description of the Omnisense Joint Timing and Location Engine (JTLE) for positioning and locating things.

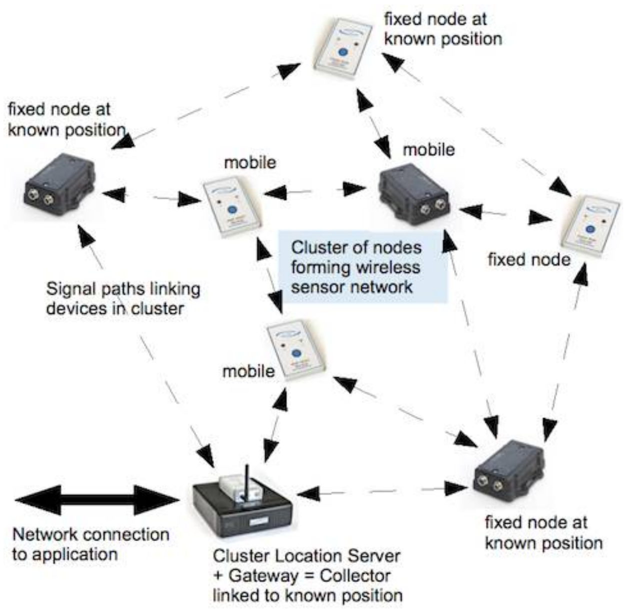
ToA Architectures

In a ToA system all (or some) of the devices (nodes) transmit a radio signal, which we refer to as a chirp, which any permitted neighbour within radio range can receive, measure the time of arrival and decode the payload. This is a one-to-many broadcast architecture with nodes both transmitting and receiving.

However, there are two subsets of this more general case:

1. A simpler mode, albeit one with significant limitations, based on point-to-point ToF (Time of Flight) measurements between pairs of nodes.
2. Architectures in which one or more nodes operate in either transmit-only (similar to conventional RFID based RTLS systems) or receive-only (similar to GPS) modes.

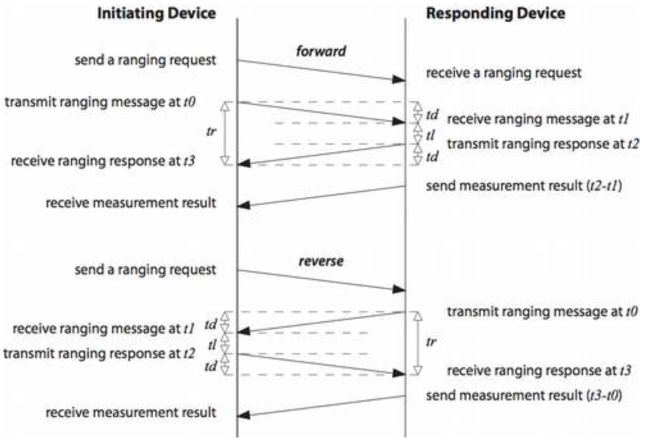
The Omnisense JTLE supports all of these architectures and can use different kinds of signal measurements as well as other information from the radio and inertial sensors in order to compute the positions and attitudes of the nodes.



Requirements for ToA to work

There are a few general sufficiency requirements in order to be able to compute reliable positions:

- Devices need to be within range of sufficient neighbours – in general four or more are required for a 3D position fix (3 for a 2D fix), but depending on the architecture more may be required. It is a good principle to be able to receive at least twice the minimum number required.
- It is helpful to the JTLE if devices can both transmit and receive chirps, but this is not a essential.
- Accuracy with which Time of Arrival is measured is **critical**. This is determined by the bandwidth of the signal, S/N ratio, integration time, measurement method and fidelity of the measuring circuitry.
- A sufficiently stable clock is required, the same clock being used for both transmit and receive.
- Additional radio measurements including Signal Strength (RSSI), frequency offset (Doppler), signal quality, S/N ratio as well as supplementary sensor data, such as measurements from motion sensors (accelerometer, magnetometer, gyro or altimeter) are all made use of by the JTLE.



A simple Time-of-Flight scheme

A pair of radio devices can measure the distance separating them using time-of-flight. This involves an exchange of messages between them in which the round-trip time is measured and the turn around time subtracted to yield the double range measurement.

The figure above illustrates how a ToF range is measured. It usually involves both forward and reverse measurements which are averaged to eliminate the effect of relative clock drift between the two nodes.

The ranges measured between neighbours are input to the JTLE which is able to compute their relative positions. Since the relative clock offsets and drifts are removed at the measurement stage the JTLE only needs to solve for positions and not clock offset parameters.

In a 2D planar context when a node measures the range to a neighbour at a known position the measurement represents a circle around the neighbour being the locus of all possible positions of the measuring node. Measuring a second neighbour produces a second circle from which one can deduce the position of the node as being where the two circles intersect. With only two neighbour measurements the circles intersect at either two places or none, leading to possible ambiguity in the solution. The easiest way to resolve the ambiguity is to measure a third neighbour at a known position. Three neighbours are required for 3D positioning.

ToA measurement schemes

The Time-of-Arrival of a radio signal is typically measured in one of two different ways:

- A broadband signal with a known envelope is cross correlated by the receiver. The peak of the cross correlation output represents the time offset between the two signals, the observed Time-of-Arrival. This method is often used with spread spectrum signals (CDMA), including GPS, or other wideband signals such as CSS (chirp spread spectrum) or UWB (Ultra Wideband).
- By measuring the phase of a narrow band signal, or the carrier portion of a broadband signal. The measured phase represents the observed Time-of-Arrival. This is the technique used by Omnisense's sparse wideband (SWB) and other phase measuring systems.

Computing Position with the JTLE

The Omnisense JTLE can use ToA measurements from both kinds of systems as well as simple ToF (Time-of-Flight) measurements. It also makes use of auxiliary measurements from the radio including:

- RSSI (Received Signal Strength);
- Signal quality such as bit error rate, eye quality or others;
- Doppler (frequency offset);

In the Series 500 System nodes exchange key information by transmitting it in the payload accompanying each transmitted chirp. This payload information includes some or all of the following:

- Identity of node and time;
- The current position and optionally motion trajectory of the node;
- Recent ToA measurements of neighbours and their identities;
- Transmit time of chirp if necessary (depends on radio architecture).

The JTLE uses as much information as possible to compute clock offsets of nodes and their positions. There are essentially three different levels of operation:

1. ToF for which clock offsets do not need to be estimated;
2. Classical one-way systems in which fixed devices are at known positions;
3. Full relative positioning in which any device may be mobile or fixed.

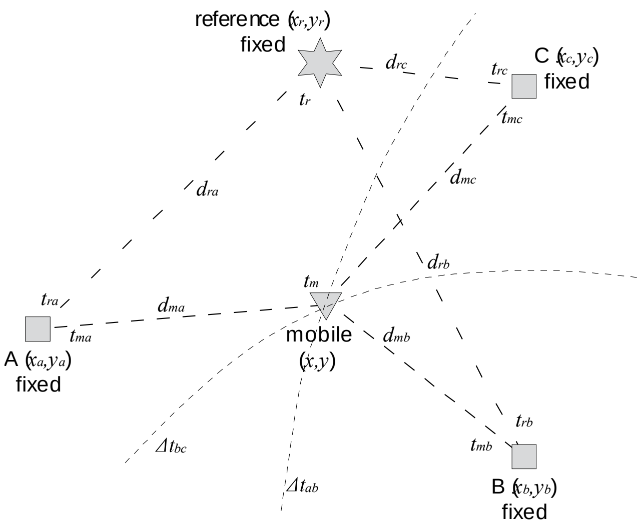
The JTLE can support mixed modes, in a single network, with different devices using different approaches.

"Classical" OTDOA positioning

In the classical architecture for RTLS a "tag" periodically transmits a signal which is received by a number of "Fixed Receivers" (also called Access Points or Anchor Nodes) which are at known locations. The fixed receivers measure the time-of-arrival of the signal from the tag and send these measurements to a "Position Processor" (Location Engine) somewhere in the network. In the most usual situation the clocks in the fixed receivers are unsynchronised so a further set of ToA measurements from a "tag" at a known fixed location are also made.

Using the measurements from the Fixed Tag, the clock offsets of the Fixed Receivers can be computed and then, assuming that the measurement from the mobile "tag" is made within the coherence time of the fixed receiver oscillators, the position and clock offset of the "tag" is solved for by the Location Engine.

The figure below illustrates the elements of this classical architecture:



Such systems sometimes operate in an "inverted" mode in which the tag measures signals transmitted periodically by the Fixed Receivers – as, for example, in cellular mobile systems using OTDOA.

The Omnisense JTLE extends these principles by combining the clock modelling with the position solution, instead of treating them separately, and through the combination of multiple time-series of chirp measurements in the solution.

Full Relative Positioning

More advanced systems in which each device in the network can both transmit and receive chirps have far more flexible architectures. For example fixed devices that can transmit to one another immediately eliminate the need for a separate Fixed Tag.

Furthermore it is possible, with additional constraints, to solve for the positions and clock offsets of all nodes relative to one another without the restriction of any being fixed. Suppose that we have N devices from which we define one as the origin (known x,y,z,t) on an arbitrary coordinate frame, we are left with 4*(N-1) unknowns to solve for (x,y,z,t) for each other device for which we have N*(N-1) measurements assuming they all see and measure all neighbours.

This is a solvable problem, and is the general case at the heart of the Omnisense JTLE. ToF systems and conventional architectures are both subsets of this general case.

Note that for the purposes of solving the positioning problem we treat it as four dimensional: x, y, z, t.

Clock Management

Given an understanding of the system parameters the Omnisense JTLE (Joint Timing and Location Engine) combines signal measurements of and from as many neighbours as possible in order to compute the clock offsets (since each node has its own independent free running clock) and the relative positions of the nodes.

The JTLE maintains a precise clock model for the node clocks. It can cope with nodes that have a discontinuous clock (shut down during sleep periods), but to get the most from these systems it is beneficial if the node transmits multiple chirps during its wake period before shutting down the clock and sleeping. The JTLE makes use of time-space diversity by using these multiple linked chirps for both clock tracking and positioning.

Performance Optimisation

The best theoretically achievable performance of positioning systems is estimated using the Cramer-Rao Lower Bound (CRLB) which is a statistical metric for the accuracy with which the ToA measurements can be made. The CRLB is bounded by three things:

1. Bandwidth of the signal being measured: bandwidth is inversely related to accuracy, so wider bandwidths lead to better resolving capability;
2. Integration time: the duration for which we observe and measure the signal;
3. Signal-to-Noise ratio: the better the S/N the more precisely we can distinguish signal from noise.

In addition to these limiting factors there are also a number of practical considerations:

- The stability of the clock;
- The fidelity of the ToA measuring circuits and algorithms;
- Other radio measurements, specifically frequency offset (Doppler), signal strength

and signal quality are beneficial to the JTLE;

- Number of neighbours used in the position computation, and the geometry of the solution;
- Extent to which multiple chirps over time-space can be integrated, and any navigation filtering that can be applied;
- Capability within radio system to detect measurement errors to assist the JTLE with signal and neighbour selection;
- Environmental factors such as multipath and interference – often the most telling factor of all;
- Sensor measurements from the integrated accelerometer, magnetometer, gyro and barometer.

The Omnisense JTLE is able to make use of this auxiliary information. Anything that helps to separate good measurements from bad ones is helpful. Most important of all is to have over-determined solutions in which more measurements than the minimum required are available. For best performance between 2 and 4 times the minimum number of neighbour measurements should be used. More than this is helpful to positioning performance but a disproportionally increasing processing cost is incurred.

Centralised or distributed LE

In many conventional systems the Location Engine is run on a centralised computing resource. All the “tag” (node) measurements are sent to this centralised device which computes their positions and provides the output to end user applications. For many tracking applications this is a reasonable architecture since it is only the application that needs to know where devices are. However, the communications bandwidth required to send back raw ToA measurements is potentially much greater than sending back processed outputs such as position.

Some systems, for example GPS, rely on the position being computed in the receiver. In this case the result needs to be sent via a suitable communications link to the application.

The Omnisense JTLE can be operated in either centralised or distributed mode depending on the requirements of the system and the capability of the node hardware. Even hybrid configurations using a combination of distributed and centralised processing can be implemented. Each approach has trade-offs which need to be taken into account when devising the optimum solution.

Application Interfaces

The JTLE provides a real-time data feed that may be consumed by end-user applications. It is delivered as JSON formatted data objects (messages) over TCP/IP. Typically the output from the JTLE will include some or all of the following:

- Device unique identifier,
- System time for fix
- x, y and z coordinates
- quality, indicator from 0 to 1, 1 is best.
- neighbours, number of devices used
- activity, mean and peak activity
- id of zone the device is located in
- ellipse, major, minor axis and angle
- attitude, orientation, pitch and roll
- temperature in degrees Celsius
- battery voltage
- parent, network parent identity

Conclusions

The Omnisense JTLE is a sophisticated state-of-the-art 10D position solver that can be used with different network architectures and measurement types. Using Time-of-Arrival radio measurements it is able to compute device positions with accurate time transfer (x,y,z,t). It is also able to make use of many supplementary measurements from the radio and other device sensors, which, in a fully featured, JTLE also yield velocity in three dimensions and orientation in three dimensions. Contextually relevant information is delivered to end-user applications using industry standard internet protocols.

About Omnisense

Omnisense Limited is a Cambridge UK based high technology business specialising in positioning assets: people, animals and other objects.

Omnisense owns IPR relating to its Cluster positioning systems and technology, including patents, designs and know-how.

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