Radio Requirements for Omnisense Relative Positioning

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Introduction

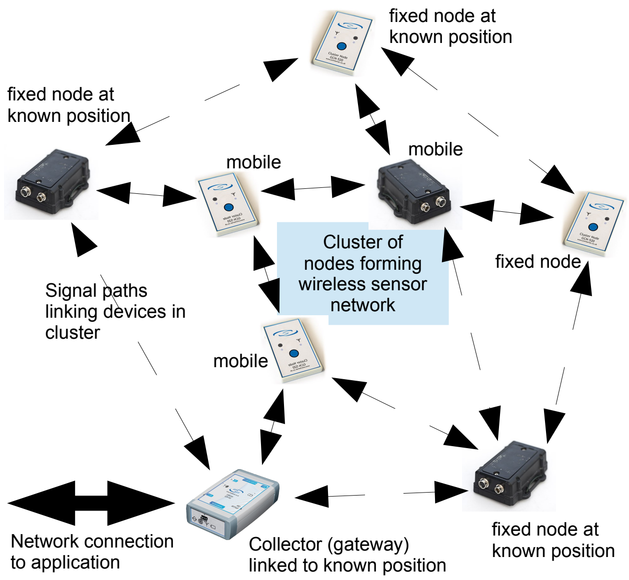
In WP001 we introduced the concept of relative positioning using collaborative techniques as used in the Series 500 Cluster location system.

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.

Computation of positions may be carried out by the node itself, or it could 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 position.

In this paper we focus on what is required from the radio subsystem in order to capture measurements that can be used by the Omnisense Joint Timing and Location Engine (JTLE) for positioning.



Principles for ToA to work

In a ToA system all (or some) of the devices (nodes) transmit a radio signal, which we refer to as a chirp, which any neighbour within radio range can receive, measure the time of arrival and decode the payload. Nodes take it in turn to transmit their chirps – this may be managed within a TDM (time division multiplex) structure, or use an “Aloha” (random access) approach.

This is a one-to-many broadcast architecture. Protocols for data flow within the network may be combined with these messages.

There is a simpler mode for positioning, albeit one with significant limitation, based on point-to-point ToF (Time of Flight) measurements between pairs of nodes. The Omnisense JTLE can also use ToF measurements.

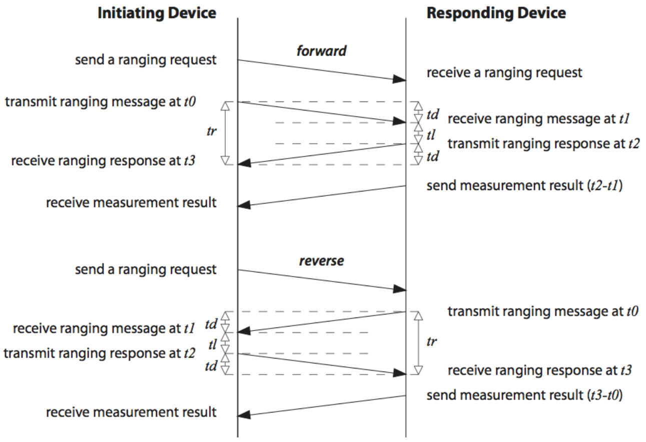
There are a few general sufficiency requirements in order to be able to compute reliable positions:

- 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 necessarily a limitation.
- 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.
- Transmit timing is as important as measuring Time of Arrival, but it is generally easier to implement.

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 below 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 were removed at the measurement stage the JTLE only needs to solve for positions and not clock offset parameters. Therefore fewer neighbour measurements are required. Nevertheless the simple ToF approach scales poorly with network size: it scales $O(N^2)$, whereas the broadcast ToA method scales $O(N)$.

Measuring ToA

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 SWB and other phase measuring systems.

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);

Clock Stability

For ToA solutions to be reliable it is imperative that the clocks at both transmitter and receiver are properly managed and sufficiently stable.

The Omnisense JTLE constructs a clock model for each device in the network. The model parameters are: Phase Offset; and Phase Drift (Frequency Offset). Both are regularly updated by an optimised phase and frequency tracking loop within the JTLE.

Since a position solution relies on combining the ToA measurements from a number of nodes, each node having measured ToA's from a number of neighbours, the clock behaviour needs to be predictable over the measurement interval with an error less than a few nanoseconds (for metre level accuracy). We call this the measurement coherence time.

Practice has shown that good quality consumer grade crystals (±10 ppm) have a coherence time of just a few seconds. Higher quality crystal oscillators can achieve longer coherence time: tens of seconds to minutes depending on cost and quality.

Furthermore during the measurement period the clock needs to run continuously without interruptions or steps. This is particularly relevant in low power applications in which the device is operated for short durations between which it is powered down to conserve battery power.

Transmit Timing

Whilst we are intent on measuring the Time-of-Arrival of neighbouring signals, if we wish to combine measurements of multiple chirps, the time at which each chirp is transmitted needs to be defined or at a known time (according to the clock of the transmitting device), otherwise each measured ToA will have a different apparent clock offset and it may be impossible to combine them in the JTLE. Being able to use multiple chirps is one of the characteristics that gives the JTLE its excellent performance.

Often each transmission occurs at time zero of the transmitting node's clock which is set to roll over repetitively on a suitable interval. For local area terrestrial systems covering a small area the base time interval can be quite short: In the early SWB radio it was 19.6923 µs (nearly 6 km). When a measurement is made it is not possible to tell which base time interval it belongs to, but only the offset within the interval – hence the need to have a sufficiently large interval to avoid ambiguity in the measurements and resulting solution.

GPS has a basic code repetition interval of 1 ms, which is assembled into data bits and frames, so even though the basic correlation code repeats every 1 ms each measurement can be placed at a unique time on an extended time scale. This level of sophistication is not needed for local positioning systems.

The choice of base time interval is a fundamental parameter in the design of the radio for a local positioning system.

Generalised ToA Approach

For ToA to work we need to satisfy a number of conditions according to the specific requirements of the application:

- A reference clock with an unambiguous interval long enough to satisfy the maximum ranges used: given radio propagation at the speed of light this equates to around 300 m per microsecond.
- Each device in the network has its own version of this clock – they do not need to be synchronised, but the stability of each clock must meet the required coherence time: every 3 ns of unpredictable clock drift introduces approximately a metre of error.
- A signal with measurable characteristics such as a known signal envelope for correlation or a defined phase behaviour is transmitted periodically.
- Signal transmissions must be at a known time: either by measuring when they are transmitted, or, more usually, by arranging for the transmission to be triggered by a defined clock event such as the beginning of the clock interval.
- A receiver that can accurately measure the times of arrival of signals from neighbours: 3 ns of measurement error translates into about a metre of position error.

The last point is actually the hardest to do, but the first four pertaining to clock management and signal transmission are often overlooked.

Location Engine

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 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. In simple ToF systems clock tracking is not required.

The JTLE is described in more detail in a separate white paper.

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.

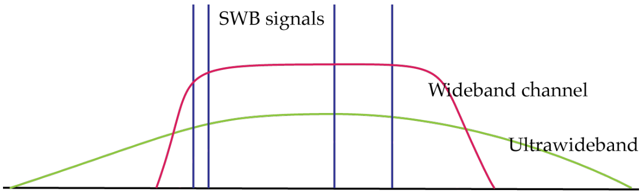
In addition to these limiting factors there are also a number of practical considerations:

- 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.

Case Study: Sparse Wide Band

Omnisense has coined the term SWB (sparse wide band) for a phase measuring technique that uses the measured phases of multiple sub-carriers within a wideband channel. Whilst the prototype radio was proprietary and used hopping between narrow band channels, the technique is one of the approaches that can be used for measuring ToA in OFDM (orthogonal frequency division multiplex) systems as used in many modern communications networks.

The essence of SWB is that the phase difference between two sub-carriers within a multichannel system (generated from the same base clock), is the same as measuring the phase of the difference frequency. By using multiple pairs of carriers with different frequency spacing one has different wavelengths for which the phase is being measured. The longest wavelength is defined by the base time interval and it defines the maximum distance that can be measured unambiguously. Larger frequency differences are used to gain higher precision in ToA measurement. This approach is simple and highly effective. It gives excellent accuracy and eliminates unknown phase offsets that are traditionally introduced into the signal carrier by the mixer and up-conversion LO in the radio transmitter.



The core parameters of the prototype SWB radio were:

- 50.78125 kHz time reference
- Nearly 400 usable sub-carriers in a 20 MHz wide channel (2.4 GHz ISM band) from 512 sub-carriers making up the 26 MHz sample rate,
- Approximately 1 ms measurement time,
- Four sub-carriers giving differences of approximately 700 kHz, 2 MHz and 10 MHz.
- Chirp repetition rates of typically 4 to 10 Hz
- Simple Aloha contention scheme
- Hopping between sub-carriers to minimise cost and complexity of tag.
- Frequency offset (Doppler), RSSI and signal quality measured and reported.

The location engine used close carrier spacings for coarse positioning and the largest spacings were used to compute the final high resolution position. Multiple chirps from each tag are combined to give robust time-space diversity to the solution, with performance at the 0.5 m level outdoors, over ranges up to 1 km. Doppler and signal quality were used to provide positioning confidence and a direct estimate of velocity.

This SWB implementation is equally applicable in OFDM systems in which phase measurements of the pilot sub-carriers are used in the JTLE instead of the hopped tones of the bespoke SWB radio described above. Most standards-based OFDM radio PHY's have sufficient pilot channels and the channel spacing between pilots tends to be well suited for positioning use.

Another of the major strengths of the system described is the fact that it is frequency agnostic. Even though the first implementation uses 2.4 GHz, the same approach could be used in any suitable available frequency band, subject to the usual constraints of bandwidth and radio regulations.

Conclusions

The Omnisense JTLE has been used with a number of different radios including a custom designed SWB radio and commercially available integrated circuits with phase, ToA and ToF measurements. With proper clock management, transmit timing and the ability to measure accurate time of arrival in the radio, the Omnisense JTLE can almost certainly provide a positioning solution.

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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