

Considerations and Challenges in Real Time Locating Systems Design

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Abstract—Real Time Locating Systems (RTLS) are a combination of hardware and software that are used to continuously determine and provide the real time position of assets and resources equipped with devices designed to operate with the system. There are many applications calling for RTLS, particularly now that it has become affordable and mobile wireless devices have become small and convenient. This paper discusses some of the possible technologies and algorithms to be considered when designing these systems and highlights some of the important challenges faced by this industry.

I. INTRODUCTION

Real Time Locating Systems (RTLS) are a combination of hardware and software that are used to continuously determine and provide the real time position of assets and resources equipped with devices designed to operate with the system. Future RTLS systems are envisioned to be based on low power electronic tags used to track and/or monitor assets, people or anything of value with very high accuracy and mobility. For example, a current application of RTLS is asset tracking in hospitals, where valuable equipment can be instantly located anywhere in the area covered by the network by a central location engine stored on a central server. The market for RTLS systems is expected to grow to 2.7 billion dollars in 2016 [1]. And new innovative RTLS and Location Based Services (LBS) technologies should even increase this.

However, current RTLS tags suffer from two major drawbacks. Wideband based tags provide accuracy but typically are energy detector based systems with limited range, while relatively narrowband based tags do not provide the accuracy some applications require. The second major drawback is that the tags can be large and power hungry. The goal of RTLS design is to eliminate this complicated tradeoff between accuracy, power consumption and range.

This paper is arranged as follows. In section II, some of the possible algorithms for RTLS are discussed, with details of the desired wireless signal properties, and the advantages and disadvantages discussed. Section III gives a detailed description of time of flight and time of arrival ultrawideband systems. A number of the major challenges faced by RTLS systems are highlighted in section IV and the conclusions are given in section V.

II. RTLS ALGORITHMS

Fundamentally, RTLS algorithms can be divided into three classes: algorithms which aim to estimate the distance between

the tag and the application point¹, algorithms which use arrival angle at the application point and algorithms which use a combination of both. In addition, the central location engine may have *a priori* information on the environment, such as a detailed floorplan with obstructions or a channel sounding database, which allows the algorithms to produce a more accurate estimate of a tags location.

A. Estimating the distance between a tag and application point

A popular technique in RTLS is to estimate the distance between a tag which transmits a packet and a application point which receives this packet. Using multiple application points, the location of the tag can be estimated from some form of trilateration (or higher order) algorithm [2].

However, there are multiple possible system level methods of estimating this distance.

The first to be discussed is the received signal strength (RSS) technique. This uses an estimate of the energy of the received signal to estimate the distance that the signal has traveled. By assuming some path loss exponent n , the estimate of the distance can be calculated from the following relation

$$\hat{P}_{RX} = P_{TX} - 10n \log_{10} \left(\frac{\hat{d}}{d_0} \right) - PL_0 \quad (1)$$

where \hat{P}_{RX} is the estimate of the received power in decibels (dBs), P_{TX} the transmitted power in dBs, d_0 is the reference distance which has a path loss of PL_0 dBs and \hat{d} the estimate of the distance.

This method has some advantages. In theory, the accuracy is often assumed to be independent of the bandwidth of the signal. Hence, popular preexisting networks can be utilised. For example, a WiFi network can be used with additional software and WiFi based tags to produce a RTLS system. This is a huge advantage due to popular deployment of WiFi and is popular in current RTLS products [3].

However, using the expression in equation 1 to obtain \hat{d} has two major problems which affects accuracy significantly. The first is that the path loss exponent n is unknown. This typically can range from 2-6 in WiFi channels and without an extremely accurate estimate of this value, the estimate of the distance can

¹In this paper, the term tag refers to the transceiver which is to be located and application point refers to the transceiver which is a known point of reference.

have a significant error component. The second problem is the constructive and destructive interference present in almost all wireless channels. With a relatively small bandwidth, this interference can cause a large variation in the received power over the expected value.

Techniques exist to combat these two issues, but to date, do not produce a mean accuracy less than 5 meters.

The second possibility for estimating the distance between transmitting tag and receiving application point is using an estimate of the time of flight. Given an estimate of the arrival time at the receiver \hat{t}_{rx} and information on the transmit time at the tag t_{tx} , the estimate of the distance between transmitter and receiver can be calculated as

$$\hat{d} = (\hat{t}_{rx} - t_{tx})c \quad (2)$$

where c is the speed of light.

This technique has the advantage that it is much more robust to the multipath channel than the RSS technique. By assuming that there is a direct path between transmitter and receiver and that the clocks in both transmitter and receiver are synchronised (i.e. \hat{t}_{rx} and t_{tx} are from the same reference clock), the estimate \hat{d} can be extremely accurate. However, neither of these of these assumptions are trivial.

Assuming a direct path between transmitter and receiver carries some important system design choices. Firstly, in a wireless channel, obstructions can cause this path to be extremely heavily attenuated. Steps must be taken in order to be able to resolve this attenuated path in the presence of noise. Secondly, the direct path should be as free of constructive and destructive interference as possible. Destructive interference can render an already attenuated path undetectable at the receiver. Thirdly, and most importantly, to get a very accurate estimate of the time of arrival, the transmitted signal must have a very fast leading edge rise time. Of course, the faster the rise time, the larger the bandwidth. All of these issues justify the growing interest of ultrawideband (UWB) signals (greater than 500MHz) for RTLS, where the signal is extremely robust to constructive and destructive interference as shown in figure 1 (assuming that an energy detector based receiver is not used) and where an UWB pulse has a very fast rise time. However, low power UWB receivers are more difficult to implement than conventional narrowband systems due to the high sampling rates required.

The second assumption on the synchronisation of clocks is of concern no matter what the bandwidth due to clock differences which are caused by crystal effects. This assumption will be set aside until section III where UWB RTLS will be discussed in detail.

B. Using the Angle of Arrival (AOA) to estimate a transmitters location

The second technique in RTLS uses the angle of arrival to estimate the orientation of the transmitter relative to the receiver. By measuring the difference in arrival times of a signal on the elements of an antenna array, the direction of

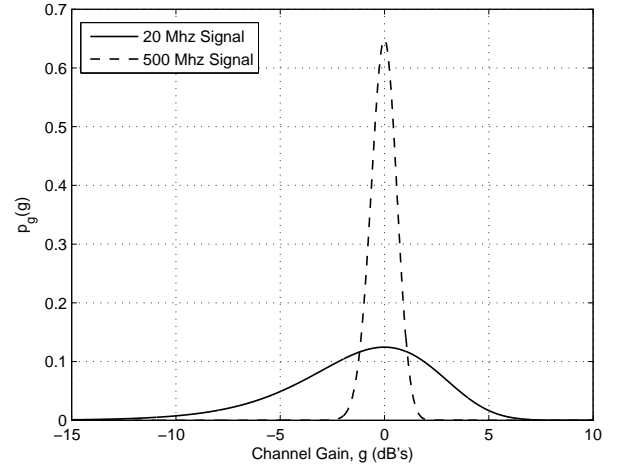


Fig. 1. Channel gain for ultrawideband and relatively narrowband channels for a channel with large delay spread (≈ 250 ns). Channel gain is defined here as the resulting energy gain due to constructive and destructive interference.

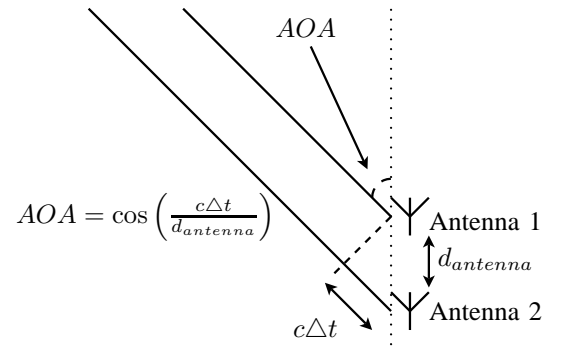


Fig. 2. An angle of arrival system using two antennas. By utilising the difference in the time of a arrival of a signal at the antenna pair (Δt) along with the antenna spacing $d_{antenna}$, the arrival direction can be estimated.

arrival can be estimated as in figure 2. This can be viewed as the reverse of beamforming.

One of the main issues with AOA systems is the need for multiple antennas (and accompanying RF front ends) at the receiver. For carrier frequencies less than 10GHz, where most wireless systems exist, the antenna size can be quite large. Multiple antennas increase the form of the receiver, leaving it somewhat unattractive. In addition, the angle of arrival of a narrowband signal is largely dependent on the dominant path which may not be the direct path. This leads to an error in the arrival angle (which could be anywhere from $-\pi$ to π from the correct arrival angle) and can lead to a significant error in the location estimate.

Combinations of the discussed techniques exist, but are outside the scope of this paper which is intended as an introduction to the techniques. Also, interested readers are directed to a MATLAB tool set called the Sensor Network Localization Explorer (SeNeLex) which demonstrates the different methods [4].

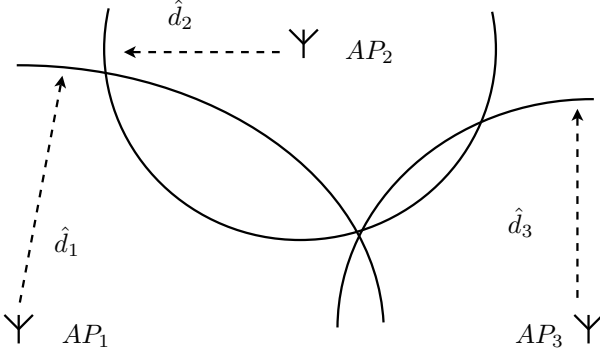


Fig. 3. Example of using 2D trilateration for locating a tag. By estimating the distance between the tag and each of the three application points (TOF/RSS), the location of the tag can be estimated by finding the intersection of the three circles.

III. UWB FOR PRECISION LOCATING

As discussed in section II, there are multiple system design considerations for RTLS. In this section UWB systems combined with two related, but different, approaches to precision locating of tags will be discussed in detail [5].

The first is commonly known as Time of Flight (TOF) or Time of Arrival (TOA). In this system the time of flight is measured at three application points². Let $\hat{\tau}_n$ equal the estimate of the time of flight between the tag and application point n , (x_n, y_n) be the location of application point n (in cartesian coordinates), which are known to the CLE and (x_t, y_t) be the location of the tag, which is the unknown of interest.

Estimating the location of the tag is equivalent to finding the intersection of three circles, as in figure 3. These circles are given by the following set of equations

$$(\hat{\tau}_1 c)^2 = (x_1 - x_t)^2 + (y_1 - y_t)^2 \quad (3)$$

$$(\hat{\tau}_2 c)^2 = (x_2 - x_t)^2 + (y_2 - y_t)^2 \quad (4)$$

$$(\hat{\tau}_3 c)^2 = (x_3 - x_t)^2 + (y_3 - y_t)^2. \quad (5)$$

This is called trilateration. Trilateration is a method of determining the relative positions of objects using the geometry of triangles in a similar fashion to triangulation. Unlike triangulation, which uses angle measurements (together with at least one known distance) to calculate the tags location, trilateration uses the known locations of two or more application points, and the measured distance between the tag and each application point.

²Throughout this paper, we will assume two dimensional (2D) locating. This clarifies the mathematics involved with the need for only three application points. However, an increase to three dimensions only requires an additional application point.

However, this algorithm requires that all the tags and application points have the same reference clock. Considering crystal effects, this requirement is hard to achieve. Ideally the tags are cheap and therefore expensive crystals are not an option. Synchronising the clocks of all devices is possible, but in an environment with a very high density of tags, this requirement reduces the network efficiency (density of the tags) significantly.

An alternative is time difference of arrival (TDOA). Consider the TOF/TOA based algorithm and the requirement that the clocks are all synchronised. At a time t_0 , the tag transmits a packet, which is received at times t_1, t_2 and t_3 at application points one, two and three respectively. the times of flight are therefore $\tau_1 = t_1 - t_0$, $\tau_2 = t_2 - t_0$ and $\tau_3 = t_3 - t_0$. The CLE has knowledge of all these times, and they are all based on the same reference clock and can therefore use a trilateration algorithm to estimate the location (x_t, y_t) .

Multilateration, also known as hyperbolic positioning, is the process of locating an object by accurately computing the time difference of arrival (TDOA) of a signal emitted from the object to three or more receivers. In multilateration the arrival time of a transmitted packet is observed at three application points, each with a known location. These application points are assumed to have the same clock. The time difference of arrival (difference in time of flight) between AP one and two is written $\Delta\tau_{12}$, which is defined as

$$\begin{aligned} \Delta\tau_{12} &= \tau_1 - \tau_2 \\ &= t_1 - t_0 - t_2 + t_0 \\ &= t_1 - t_2 \end{aligned} \quad (6)$$

Next, one of the three AP's is taken as the system origin. For example, we can assume AP three is located at $(0, 0)$. Using the relationships defined in equations 3 to 6, we can write

$$\begin{aligned} \Delta\tau_{13} &= \frac{1}{c} \sqrt{(x_1 - x_t)^2 + (y_1 - y_t)^2} - \frac{1}{c} \sqrt{(x_3 - x_t)^2 + (y_3 - y_t)^2} \\ &= \frac{1}{c} \left[\sqrt{(x_1 - x_t)^2 + (y_1 - y_t)^2} - \sqrt{x_t^2 + y_t^2} \right] \end{aligned} \quad (7)$$

$$\begin{aligned} \Delta\tau_{23} &= \frac{1}{c} \sqrt{(x_2 - x_t)^2 + (y_2 - y_t)^2} - \frac{1}{c} \sqrt{(x_3 - x_t)^2 + (y_3 - y_t)^2} \\ &= \frac{1}{c} \left[\sqrt{(x_2 - x_t)^2 + (y_2 - y_t)^2} - \sqrt{x_t^2 + y_t^2} \right] \end{aligned} \quad (8)$$

Equations 7 and 8 define the hyperbola whose intersection gives the estimated tag location (x_t, y_t) . An example of this is shown in figure 4.

However, the accuracy of both of these algorithms depends

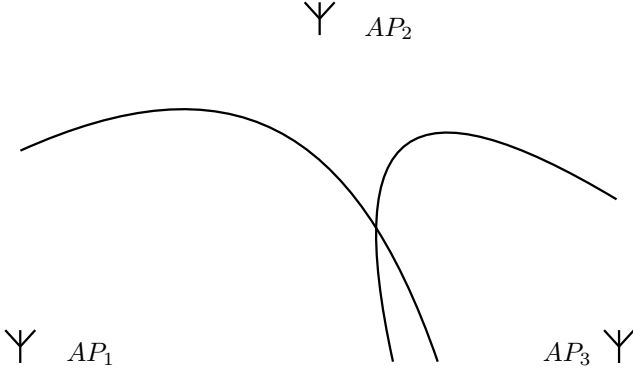


Fig. 4. Example of using 2D multilateration for locating a tag. Application point two is taken as the system origin and two hyperbola traced using the time difference of arrival values $\Delta\tau_{12}$ and $\Delta\tau_{32}$. The intersection point of these two is the location of the tag.

on the accuracy of the arrival time estimates. Errors can occur due to noise, harsh NLOS channels or interference from other tags. To achieve sub-meter accuracy, UWB pulses are necessary. Their wide bandwidth allows almost all the multipath components to be resolved, which allows the direct path to be resolved accurately and with a very fine time resolution. However, this potential accuracy requires the UWB signal to be received coherently, which require high sampling rates. This results in the significant challenge to UWB RTLS designers to design low power systems which can harness the full potential of UWB.

IV. CHALLENGES FOR RTLS

There are numerous challenges for RTLS. In this section, a small subset of these will be introduced and discussed.

A. Number of tags per network cell

Firstly, the number of tags per network cell is an important factor. Depending on the application (asset tracking in a warehouse or people tracking in a hospital) the number of tags per network cell will vary. For some applications, the large number of tags needed will be challenging to the RTLS systems.

The two main factors when considering tag density is the duration of the transmitted packet and the rate of transmission (blink rate). The number of packets receivable, N_{tags} , per blink rate period is calculated from

$$N_{tags} = \frac{eB_R}{T_P} \quad (9)$$

where e is the efficiency of the network protocol (for example 0.184 for the aloha protocol), B_R is the blink rate in seconds and T_P is the length of the packet in seconds. By reducing the length of the packet, the number of tags can be increased. However, each packet must contain a certain amount of information (for example, a tag identification number), so the length of the packet is dictated by the data rate of the system. Hence, high data rates are desirable.

By increasing either e or B_R in equation 9, the number of tags can also be increased. These two values can actually be considered to be closely related. If we assume some network protocol which allows a certain confidence in receiving packets (i.e., a protocol which results in a certain percentage of collision free packets) would need to be employed in combination with a blink rate which allows the loss of packets. As an example, if a network protocol results in the loss of five percent of the packets through collisions, over two blink intervals only 0.25 percent of the packets have not been received in either interval. If the blink interval is short enough (which is dictated by the required tracking speed), this loss maybe acceptable and results in a large increase in the overall number of tags while retaining the tracking speed.

B. Long battery life

An important challenge for RTLS is designing a system which is of low enough power to ensure that the battery lasts long enough for the required application. Ideally, a tag should be small enough to tag an asset unobtrusively and with a battery life of the order of years so that it does not need to be replaced. This challenges the system design to deliver on the potential performance, while using as little power and silicon area as possible.

C. Channel environment

However, the most significant challenge to any RTLS device (be it narrowband or UWB) is the channel environment. Most environments result in a significantly degraded received power and impulse response as the distance between transmitter and receiver increases. This limits the possible range of RTLS and their performance. Increasing the signal bandwidth can reduce the channel effects somewhat (or, at least, make them consistent), but concrete walls and metallic objects/structures still degrade the accuracy in the estimate of the location. This presents significant challenges to both system level and software design. In addition, the antenna adds distortion to the signal waveform, which introduces a challenge for antenna designers.

V. CONCLUSIONS

This paper discusses some of the important system design considerations and challenges in real time locating systems. The two main methods (distance between transmitter and receiver and angle of arrival) used in estimating the location of a transmitting tag were introduced and discussed. This is followed by a detailed discussion of time of arrival based algorithms and their use in estimating the distance between transmitter and receiver. Comparison of the different methods shows that each have their associated advantages. RSS schemes using narrowband transceivers (WiFi) are a good solution where the infrastructure is pre-existing and battery life is not a major concern. However, it was clearly shown that ultrawideband signals are essential to achieve the sub meter accuracy required by many applications. Finally, some of the major challenges to RTLS system design were highlighted and their impact on the system design described.

REFERENCES

- [1] P. Harrop, G. Holland and R. Das, "Real Time Locating Systems 2008-2018," *IDtechEX report*, www.idtechex.com.
- [2] N. Bulusu, D. Estrin, L. Girod and J. Heidemann, "Scalable Coordination for wireless sensor networks: Self-Configuring Localization Systems," *In Proceedings of the Sixth International Symposium on Communication Theory and Applications (ISCTA 2001)*, July 2001.
- [3] H. L. Moen and T. Jelle, "The Potential for Location-Based Services with Wi-Fi RFID Tags in Citywide Wireless Networks," *4th International Symposium on Wireless Communication Systems (ISWCS)*, Oct. 2007, pp.148-152.
- [4] "The Sensor Network Localization Explorer", <http://www.ece.osu.edu/ashj/localization/>
- [5] "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks (WPANS). Amendment 1: Add Alternate PHYs." *IEEE Computer Society*, Annex D.