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Robert J. Fontana, Edward Richley, JoAnn Barney

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Robert J. Fontana, Edward Richley, JoAnn Barney

Multispectral Solutions, Inc.

Germantown, MD USA

Tel: +01 301.528.1745 Email: (rfontana,richley,jbarney)@multispectral.com

ABSTRACT

Ultra wideband (UWB) technology has been shown to possess unique advantages for precision localization applications. The use of short pulse RF waveforms provides inherent precision for time difference of arrival measurements, as well immunity to multipath effects in indoor applications. This paper describes an FCC-approved, commercial UWB Precision Asset Location system which is being used for tracking of high valued assets in hospitals, factories and in military facilities.

1. INTRODUCTION

Perhaps one of the more important applications for ultra wideband (UWB) technology is that of precision asset location and tracking. The reasons for this are many. From a technical perspective, UWB offers unmatched performance in providing 2- and 3-D precision localization (to subfoot resolutions) even in the presence of severe multipath [1,2]. This is due to the use of short, nanosecond duration, pulses whose time-of-flight can be accurately determined with the use of sensitive, high speed detection circuitry which can trigger on the leading edge of the received waveform [3]. From a regulatory perspective, UWB precision asset location systems, because of their reduced data rates, can utilize significantly higher peak powers than those allowable for high data rate (e.g., communications) systems when operating under the new Federal Communications Commission (FCC) regulations for UWB emissions (47 CFR Part 15 Subpart F) [4]. Thus, a UWB tagging system can operate over significantly longer ranges indoors, as compared with a system designed for high data rate communications. In addition, the extremely low duty cycle waveforms used for this application have the added advantage of extreme longevity of operation with small, coin-size batteries. Operational lifetimes in excess of 3.8 years have been demonstrated using a single Lithium cell.

In this paper, we discuss the implementation and performance of the first *commercial* UWB precision asset location system. The system, nicknamed *PAL650*, has been FCC certified to be compliant with the new UWB rules. *PAL650* is currently being deployed for asset location in hospitals and industrial facilities.

2. PAL650 DESCRIPTION

The *PAL650* UWB Precision Asset Location system consists of a set of active UWB tags (one of which is used as a calibration or reference tag), UWB receivers and a central processing hub. The hub interfaces with an external computer (for user display and running of application software) via either serial RS-232 or Ethernet. These components are illustrated below in Figures 1-3.



Figure 1. *PAL650* UWB Active Tag with Radome



Figure 2. *PAL650* UWB Receiver (Ceiling Mounted)



Figure 3. *PAL650* Central Processing Hub

The UWB active tag operates at a center frequency of 6.2 GHz and has an instantaneous -10dB bandwidth of 1.25 GHz. A picture of the antenna side of the tag electronics (with copper groundplane) is shown in Figure 4 below. A broadband monopole design was used to

achieve the requisite bandwidth. The tag is $1\frac{7}{8}$ inches in diameter and $\frac{7}{8}$ inch high at its widest point (unpacked). With its polyethylene radome housing, the tag diameter is 2 inches and height $1\frac{1}{8}$ inches. The tag operates at 3.0 volts with a current consumption of approximately 30 microamps. With the Lithium (CR2477) cell battery illustrated (3.0V 1A-hr), the life expectancy for the tag is in excess of 3.8 years. Further details on the RF properties of the tag are provided below.



Figure 4. Antenna side of PAL650 tag

The PAL650 UWB receivers consist of two separate boards, one containing the C-band RF electronics and high speed UWB detector and the other containing control and interface electronics (cf. Figure 5).

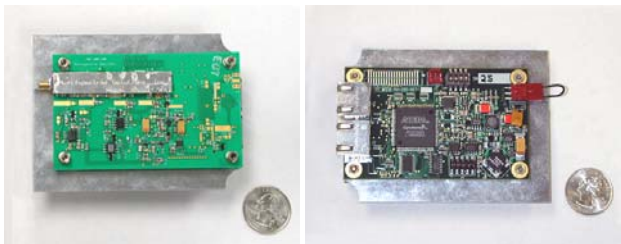


Figure 5. PAL650 Receiver RF (left) & digital boards

A simplified receiver block diagram is illustrated in Figure 6 below. A wideband, low insertion loss, microstrip filter and PHEMPT low noise amplifier provide the input to a high speed, tunnel diode detector. The tunnel's superb performance at low RF levels makes it an ideal device for achieving leading edge detection on short microwave bursts. After baseband amplification and pulse conditioning, a time-of-arrival (TOA) measurement is made to 1 nanosecond resolution through the use of a tapped delay line and FPGA-based comparator. Finally, raw TOA data is transmitted to the hub processor, either directly or via a daisy-chain loop through other remote receivers.

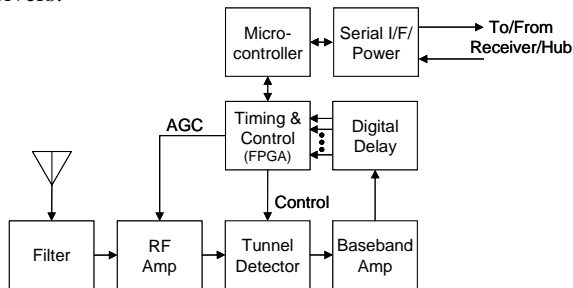


Figure 6. PAL650 Receiver Block Diagram

The receiver board dimensions are $2\frac{3}{16} \times 3\frac{9}{16}$ inches with a 1 inch height, and the overall receiver housing dimensions $2 \times 3\frac{1}{4} \times 6$ inches. The shielded compartment in Figure 5 contains the low noise (0.5 dB NF) receiver front end. Antennas used for the receiver have included both wideband corner reflector and patch designs. Figure 2 above illustrates a patch antenna configuration with +5 dBi gain.

The receivers obtain their power from the central processing hub (Figure 3) via standard CAT-5 cables, which are also used to carry data back to the hub for subsequent processing. In the configuration described in this paper, the receivers are simply daisy-chained together; however, a hub-spoke configuration has been designed for the next version to eliminate the potential for a single point of failure in serial communications and power distribution to each of the receivers. The hub uses a standard single board computer and custom interface card for serial data and power distribution.

The system operates as follows. A set of three or more receivers (typically four receivers are used) are positioned at known coordinates within, or about the periphery of, the area to be monitored. Figure 7 illustrates an Multispectral Solutions, Inc. (MSSI) laboratory configuration in which a set of four receivers are located on the vertices of a square which is approximately 40 feet x 100 feet in dimensions.

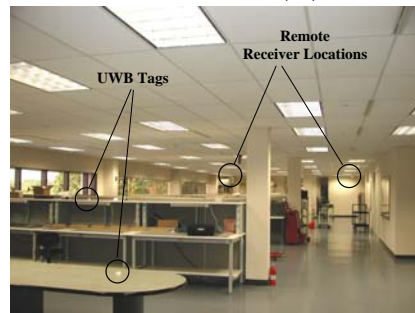
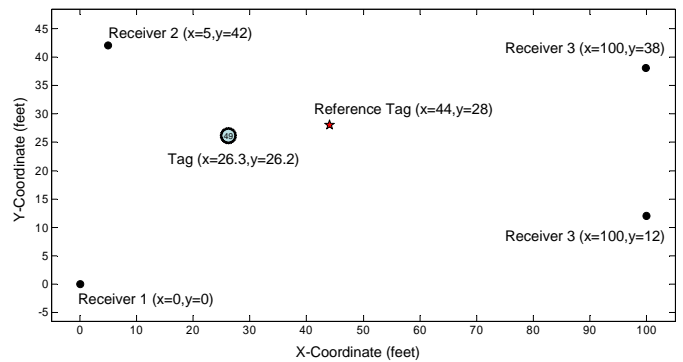


Figure 7. MSSI Engineering Lab Tag Deployment

Short pulse, radio frequency emissions from the tags are subsequently received by each (or a subset) of these sensors and processed by the central hub CPU. A typical

tag emission consists of a burst of 72 pulses (bits) at a 1 Mb/s burst rate. The RF burst includes synchronization preamble, tag ID, optional data field and forward error correction and control (FEC) bits. In the present configuration, the tag data repeats once every second;

$$\varepsilon = \sum_{j=1}^N \sum_{k=j+1}^N \left\{ (t_j - t_k) - \frac{1}{c} \left[\left[(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2 \right]^{1/2} - \left[(x - x_k)^2 + (y - y_k)^2 + (z - z_k)^2 \right]^{1/2} \right] \right\}^2 \quad (1)$$

however, rates of up to approximately 5200 updates per second can be accommodated without exceeding FCC Part 15 limits (see also [4]).

Time differences of arrival (TDOA) of the tag burst at the various receiver sites are measured and sent back to the central processing hub for processing.¹ Calibration is performed at system startup by monitoring data from a reference tag which has been placed at a known location. Unlike one existing commercial spread spectrum-based geolocation system, the current system does not rely upon the use of precision cable runs for the relay of RF signals; rather, standard CAT-5 cables are used to carry digital data from the receivers back to the hub.

One problem that is unique to asset tracking systems is that, in order to accurately determine tag position, a minimum number of receivers (typically three) must have a direct line-of-sight or at most an attenuated line-of-sight, transmission path. However, due to the nature of the indoor environment, there may only be a limited number of such direct transmission paths. For example, walls, machinery, containers, and other materials may create signal attenuation or even complete signal blockage. Thus, there may exist certain zones within the operating area of interest in which position accuracy may be degraded for lack of adequate signal reception. One solution to this problem is to provide a set of redundant sensors. However, in doing so; it now becomes possible, and in fact often very likely, that more than the minimum number of sensors will receive a given transmission. Such a system is often referred to as an "over-specified" or "over-determined" system. A potential drawback of using an over-determined system relates to the fact that hyperbolic ranging algorithms can calculate more than one mathematically valid position. That is, gross ambiguities in position determination can arise. Various techniques have been applied to address this ambiguity issue (e.g., pre-filtering [5]). Here we use an alternative approach which applies gradient search and steepest

descent algorithms to minimize an appropriate error functional.

In the first optimization technique, the following error functional was minimized

where N is the number of receivers, c is the speed of light, $x_{j,k}$, $y_{j,k}$, and $z_{j,k}$ are the coordinates of the receivers and $t_{j,k}$ are the arrival times received at each of the receivers. Note that only time differences are required. The starting point for the minimization is obtained by first doing an area search on a coarse grid of x, y and z over an area defined by the user. This is followed by a localized steepest descent search.

A second error functional is defined by the relationship:

$$\varepsilon = \sum_{j=1}^N \left[\left[(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2 \right]^{1/2} - c(t_j - t_0) \right]^2 \quad (2)$$

where time and position differences are replaced by their non-differential values by incorporating an additional unknown dummy variable, t_0 , which represents an absolute time epoch. The starting point for this algorithm is fixed at the geometric mean position of all active receivers. No initial area search is needed, and optimization proceeds through the use of a Davidon-Fletcher-Powell (DFP) quasi-Newton algorithm [6].

The current software version provides for either of the above algorithms to be implemented via a configurable switch which is stored along with other global parameters on the hub's compact flash. An additional switch is provided to force two dimensional calculations for either method, even if the tag transmissions are visible on more than 3 receivers.²

Both of these methods are demanding in terms of CPU requirements; however, the current Linux-based 400 MHz Alchemy™ Au1500 AMD MIPS32 processor can accommodate over 100 simultaneous tags at the current tag update rate of once per second. In most cases of practical interest, one tag update per second is very high –

¹ Systems based upon TDOA are sometimes referred to as either "multilateration" or "geolocation" systems; terms which refer to the process of locating a signal source by solving for the mathematical intersection of multiple hyperbolae determined by the difference of arrival times between signals received at multiple sensors.

² Note that, in order to obtain accurate 3-D position data, the receivers must be distinctly separated in both the vertical direction as well as in the x-y plane. This is a problem that is well known from the Global Positioning Satellite (GPS) system – vertical dilution of precision (VDOP).

typical blink rates being from once every 5 seconds to once an hour [7].

3. FCC COMPLIANCE

The *PAL650* RF Tag complies with the requirements of §15.117(b). A bandwidth plot is shown in the following figure. Note the operational center frequency of 6.191 GHz and the UWB (i.e., -10 dB) bandwidth of 1.25 GHz. A -3dB bandwidth of approximately 400 MHz yields an instantaneous pulsewidth of roughly 2.5 nanoseconds. As shown below, position resolution to better than one foot has been achieved (without averaging) suggesting that the receiver operates on the leading edge of the received pulse in high signal-to-noise ratio environments.

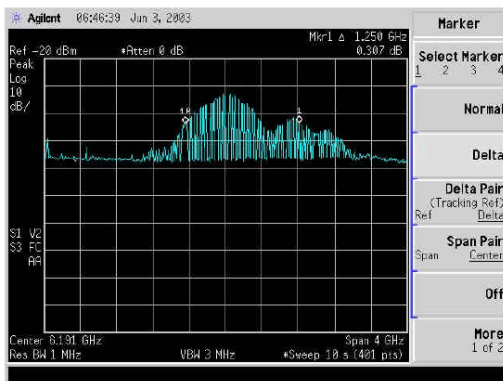


Figure 8. Measured *PAL650* Power Spectral Density

Peak and average power emissions were measured by an independent test facility (Met Labs, Baltimore, MD) and are summarized in Table 1 below.

TABLE 1
Measured Emissions (Peak & Average)

Device	Peak ^(*)	Average ^(*)
<i>PAL650</i>	58.13 dB μ V/m	39.01 dB μ V/m ^(**)
<i>FCC Limit</i>	61.2 dB μ V/m	53.9 dB μ V/m

^(*) All measurements were performed with a 1 MHz RBW and referenced to a 3 meter range.

^(**) The DUT average measurements represent the spectrum analyzer noise floor (see discussion below).

As indicated above, *PAL650* transmits a 72 bit burst at a 1 MHz rate (71 μ s duration) and then turns off for the remainder of an approximately 1 second interval before transmitting the next burst. As pointed out in [4], the *measured* average emissions do not accurately represent the device under test, but rather reflect the spectrum analyzer noise floor. The true average EIRP for *PAL650* can be calculated to be 16.1 dB μ V/m as measured in a 1 MHz resolution bandwidth. This value is approximately

4. Performance Results

As noted in the previous section, the UWB tags generate a peak electric field strength intensity of 58.13 dB μ V/m at a 3 meter distance as measured in a 1 MHz resolution bandwidth. This translates to a -37.1 dBm/MHz EIRP. As the measured -3 dB pulse bandwidth is 400 MHz, the full bandwidth EIRP is approximately $-37.1 + 20 \log(400)$ dBm = 14.9 dBm, or roughly 30 milliwatts. The UWB receiver noise figure at 6.2 GHz is 0.6 dB using a low noise PHEMPT design, resulting in a system noise floor of -87.4 dBm. The detector uses a tunnel diode for high sensitivity, and can operate with signal-to-noise ratios as low as +8 dB. With a link margin of $(14.9 - (-87.4)) - 8 = 94.3$ dB, line-of-sight range is calculated in excess of 650 feet. An outdoor experiment with the tag and tag reader verified a range of 600 feet, in good agreement with the calculated results. Indoors, the range is further limited by attenuation from walls, partitions and potential blockages; however, ranges in excess of 200 feet have been demonstrated at C-band through as many as 10 commercial-grade walls. Figure 7, for example, illustrates a 100 x 50 foot laboratory area, filled with lab bench partitions and several gypsum board/steel stud walls, which was used for the measurements below.

As discussed above, both steepest descent (with functional eq. 1) and Davidon-Fletcher-Powell (with functional eq. 2) algorithms were implemented for tag position computations. DFP outperformed the steepest descent technique, but it was more computationally intensive (cf. Table 2).

TABLE 2
Measurement Standard Deviations vs. Algorithm

Algorithm	σ (x-coordinate)	σ (y-coordinate)
Steepest Descent	0.67 feet	1.64 feet
Davidon-Fletcher-Powell	0.30 feet	0.50 feet

Note that, due to the particular geometry of the region of interest (cf. Figure 7) and the positioning of the tag receivers, the accuracy in the y-direction (vertical in Fig. 7) is expected to be worse than that in the x-direction (horizontal in Fig. 7).

Absolute positioning accuracy, of course, depends upon several factors, including precise knowledge of all receiver and reference tag locations. Absolute tag position accuracy of better than one foot has been demonstrated.

Figure 9 illustrates a typical raw data cluster (no post-processing or averaging) generated by the hub processor (7,883 data points, or approximately 2.2 hours of collected data). Figure 10 shows a histogram plot of the x-coordinate data from Figure 9. Note the peculiar effects of receiver time-of-arrival quantization. The UWB receiver utilizes a 100 MHz clock with a 10-tap digital delay line to achieve 1 nanosecond (approximately 1 foot) time resolution; however, as seen in Figure 10, the quantization “bins” are actually separated by approximately 300 picoseconds, or 0.3 feet. This is due to the effects of using time differences of arrival from four frequency-locked receivers in determining absolute position.

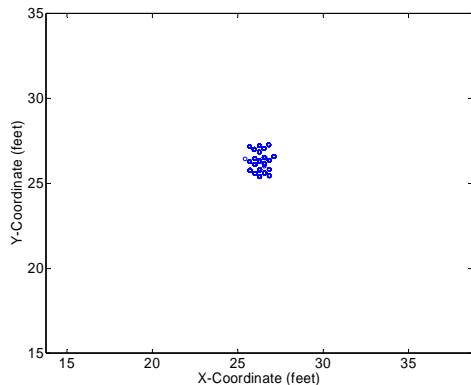


Figure 9. Raw Processed Tag Coordinate Data (7,883 data points)

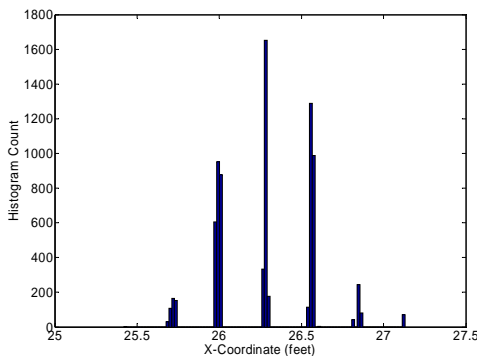


Figure 10. Histogram of Collected X-Coordinate Data

5. CONCLUSION

An FCC certified, ultra wideband (UWB) Precision Asset Location system has been described which operates in the C-band region of the spectrum (6.0-6.4 GHz). The UWB active tags make use of the unique properties of short pulse RF emissions to achieve extremely high DC-to-RF efficiency, giving the tag a battery life expectancy of over 3.8 years. A complete system consists of a set (typically 4 or more) UWB RF receivers, and a central hub processor which also provides power to the receivers and collects serial data over standard CAT-5 cables.

Unlike other systems which require the use of precision RF cables to compensate for inter-receiver delays, the present design utilizes a reference tag to fully calibrate the system. Using a 400 MHz -3dB bandwidth UWB waveform (1.25 GHz -10dB bandwidth), position accuracies of better than one foot are achievable, with standard deviations of less than 0.5 feet.

The system is currently undergoing beta testing in several hospitals and industrial facilities, and is expected to go into full scale production in the 4th quarter 2003.

6. REFERENCES

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- [7] See, for example, WhereNet’s *WhereTag II* Real Time Locating System:
<http://www.wherenet.com/download/WhereTag.pdf>