Active RFID location system based on time-difference measurement using a linear FM chirp tag signal

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Abstract— **This paper introduces a new method for estimating location of radio frequency identification (RFID) tags for application in indoor environments. The proposed positioning scheme employs a time-difference of arrival (TDOA) range estimation algorithm. The time-difference measurement is performed by taking advantage of the de-ramp properties of a linear frequency modulation (LFM) chirp. The paper provides details of the mechanism of this LFM-TDOA scheme from the system point of view. Compared to other popular radio technologies in the indoor positioning field, this new scheme is easy to design and requires only moderate computation ability. According to the experiment results summarized in the paper, the LFM-TDOA system shows good range estimation accuracy and thus has the potential to be used in accurate indoor location application.**

Keywords- chirp, FFT, indoor location, LFM, RFID, time-difference-of-arrival

I. INTRODUCTION

The interest in indoor real-time location sensing systems has been growing in recent years. [1] Although some principles are very similar to the well-known Global Positioning System (GPS), indoor location sensing focuses on the application inside large scale buildings where GPS is unable to work reliably. Active RFID is one of many technologies (such as WLAN, UWB, and Bluetooth) considered as potential solutions in the indoor location application. This paper proposes a new active RFID location method that employs a linear frequency modulated (LFM) signal for time difference of arrival (TDOA) measurement. The idea is demonstrated through a prototype RFID location system working in the 2.4GHz ISM band.

The LFM signal is also known as chirp signal whose frequency linearly varies over a wide band of spectrum, either increasing or decreasing, with time. It is a classic approach to execute time-of-arrival (TOA) measurement in FMCW radar [2] where a LFM waveform is transmitted to locate targets. The echo reflected from a target consists of a replica of the transmitted LFM signal (Fig. 1(a)) but delayed by $\tau = 2r/c$, where r is the target range and c is the propagation velocity. Mixing the target echo with the local oscillator (LO) chirp will yield a signal with a constant frequency equal to the frequency difference between the two inputs. By analyzing the spectrum of the mixer output, the range information can be obtained as the output signal frequency is proportional to the target range. (Fig. 1(a))

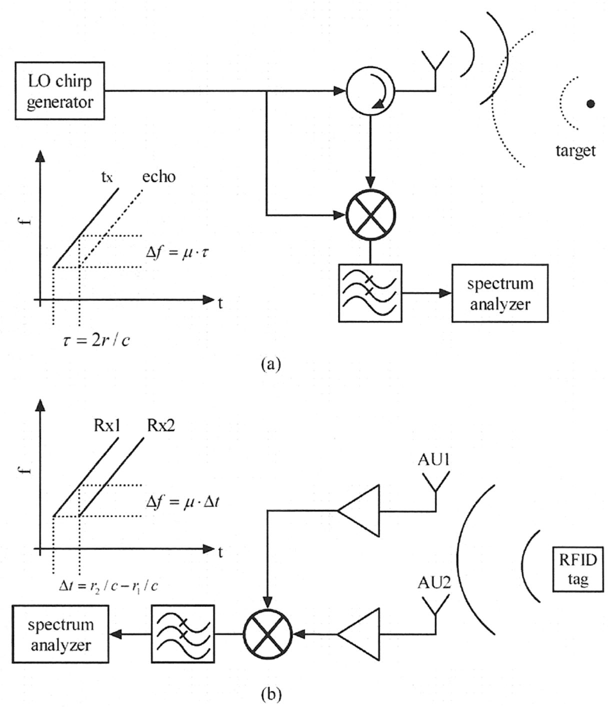

Figure 1. LFM signal measurement for (a) time-delay between transmitted signal and echo, (b) TDOA between arrival signals to a pair of AU

This traditional method takes advantage of the linear frequency variation feature of a LFM chirp to derive the time delay between the transmitted waveform and received echo. But the time measurement ability of LFM chirp is not limited to this application. Instead of generating the chirp waveform in the radar transceiver, the proposed TDOA scheme implements the chirp generation in an active RFID user tag and uses the base stations as listen-only receivers. In this case, the tag

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transmits the LFM chirp and then the received signals at a pair of base stations are mixed in a central unit in order to find the differential time delay between them. (Fig. 1(b)) From the network point of view, a number of base stations are deployed around the indoor environment to monitor the area of interest and an infrastructure is needed to connect all base stations in order to derive the time difference information. One possible solution is using an RF-over-fibre technique [3] to construct the infrastructure so that the base station can be a simple antenna unit (AU).

In the indoor scenario, the TDOA location scheme has a few advantages over the TOA measurement used in classic FMCW radar. Firstly, the targets of interest are the users carrying the RFID tags, other than a radar target that will backscatter the signal. Therefore, employing pulsed and coded LFM tag chirp waveforms allows both location and identification of users. Secondly, with TDOA measurement, location estimation is achieved by estimation of time difference between received signals other than exact time delay. Such a system avoids the need for synchronization between base stations and thus offers simplicity of tag and receiver design. Also, due to the fact that the wideband chirp signal is generated in the tags, this approach does not require very fine frequency stability.

On the other hand, the TDOA indoor location scheme raises new issues that are different from the classic range estimation method using LFM chirp. There is no reliable and clean LO input to the mixer; instead, both received signals Rx1 and Rx2 come through the air channel. (Fig. 1(b)) They radiate in the same environment but transmit along different paths. Therefore, both Rx1 and Rx2 experience some degree of attenuation, noise degradation from active devices, multipath effects, and possibly distortion in antennas and filters. Secondly, TDOA measurement is an indirect way of estimating location. This indirect measurement thus requires more receivers to achieve the same degree of location information.

In this paper, we will firstly describe, in section II, the structure of an indoor active RFID location system. Section III will begin with a brief summary of existing radio techniques for indoor location and then introduce the new LFM-TDOA method as a potential alternative technique. In section IV, we show a proof of concept experimental arrangement and results. Finally in section V, we conclude the work presented in this paper and discuss the further work needed to optimize the system.

II. INDOOR ACTIVE RFID LOCATION SYSTEM

This section introduces the structure of an active RFID location system that is under investigation through a research project for airport applications. Therefore, the system is designed to be used in large-scale indoor environment such as an airport terminal.

In order to cover the indoor area seamlessly, base stations are deployed around the indoor area in the form of a cellular network, as indicated in Fig. 2, where antenna units are separated by around 20m and every three AUs monitor a square cell indicated by the grey shadow in the middle.

Users carry active RFID tags that transmit LFM chirps when they are moving in the monitored area. The received signals at the AUs are transmitted to a central processor to calculate the time-difference of arrival (TDOA) between every pair of AUs monitoring a given cell. The TDOA figures are then used to estimate the position of a tag transponder through a process called multilateration. That is a methodology of locating an object by utilizing the arrival time-differences of a signal sent by the object. Firstly, consider a pair of antennas in one cell. The signal emitted from an RFID source will arrive at slightly different times at two spatially separated AUs. Given the locations of the two AUs, we could find a series of tag locations that would give the same TDOA measured. The locus of possible tag locations is a hyperboloid. [4]

Within a cell, there is a third AU at a third location and it will provide another hyperboloid. The intersection of the two hyperboloids gives a line on which the tag possibly lies, as indicated in Fig. 2. The tag location can be found from the 2D point of view, if the vertical level of the tag location is known in advance. However, to uniquely determine the actual 3D location of an RFID source, a fourth antenna is required to provide an additional hyperboloid.

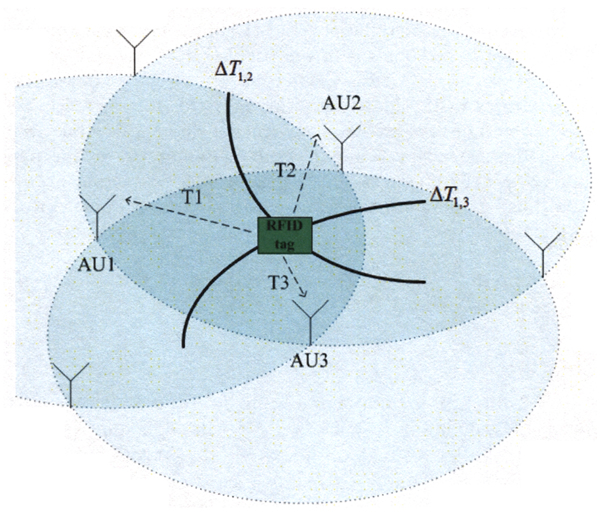


Figure 2. Deployment of antenna units for an Indoor TDOA location system; The triangle area in the middle is the overlapped cell served by AU1, AU2, and AU3.

This is the principle of location estimation based on the time-difference between a pair of received signals. The following concerns techniques to obtain this differential time delay information.

III. TDOA MEASUREMENT USING LFM SIGNAL

In the literature, there are a number of popular radio technologies discussed in the indoor location field.

A very common one is to estimate range by examining the received signal strength (RSS) of a wireless system, such as WLAN and GSM network. This method can be applied to most radio signals as it simply uses the propagation attenuation as a parameter to estimate range information. The advantage of this technique is that it can be implemented in most of the existing wireless systems thanks to its simplicity. But the accuracy of this method is poor and thus not suitable for location application that requires high precision. [5]

Direct sequence spread spectrum (DSSS) is a popular technique in location finding due to its superior performance and broad application in wireless systems. In this technique, the receiver determines time-of-flight information by correlation between a known Pseudo-Noise (PN) sequence and the input radio signal. The performance of this technique heavily depends on the chip rate of the PN sequence. Therefore, high sampling rate and strong computation ability of DSP is necessary to increase location accuracy. Low cost DSSS location capability is possible [6] at the expense of losing the real-time processing ability. However, for the purpose of monitoring a dense environment, real-time processing is desired.

Ultra-wideband (UWB) radios have relative bandwidths larger than 20% or absolute bandwidths of more than 500MHz. It has been demonstrated to be a good technique for indoor positioning. [7] The arrival time estimate using UWB signal is obtained by using a matched filter or a bank of correlation receivers at the receiver end. Due to its wide band characteristic, it is possible to provide perhaps the best location accuracy. [8] On the other hand, UWB signals used for time estimation are sensitive to clock jitter, and require higher sampling rates, which will increase system complexity and cost.

By comparison, the proposed LFM-TDOA scheme offers simplicity regarding transceiver design and efficiency in terms of location accuracy. This method uses the LFM chirp as the transmission waveform. The RFID tags transmit pulses consisting of a sequence of LFM chirps. The LFM chirps can be implemented with simple RF circuit design and low-frequency modulation techniques. At the receivers, the RF components, such as down-converter and filter, are implemented using analog techniques whereas digital processing (Fig. 4) is applied only to the de-ramp output, which requires moderate sampling speed.

To clarify the method of using LFM signal for time-difference measurement, let us consider an LFM chirp of duration Tc and swept-frequency bandwidth B. Its instantaneous frequency varies linearly with time and can be expressed as

$$f(t) = f_o + \mu t \qquad \text{for } 0 \le t \le T \tag{1}$$

where f_o is the transmitter frequency at time t=0 and μ is the chirp rate defined by

$$\mu = B / T_c \tag{2}$$

Fig. 3(a) shows the time-frequency relationship of a chirp signal and Fig. 3(b) is an LFM chirp in time domain.

The standing phase of the chirp signal can be obtained by integral of (1), assuming the starting phase at time t=0 is 0

$$\theta(t) = 2\pi \int_0^t f(t)dt = 2\pi[f_o t + (1/2)\mu t^2] \tag{3}$$

Thus, the transmitted signal can be expressed as

$$v(t) = \cos 2\pi[f_o t + (1/2)\mu t^2] \tag{4}$$

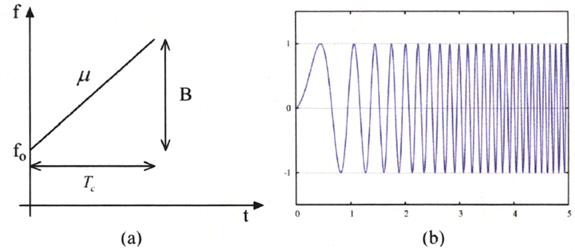


Figure 3. (a)Time-frequency feature of an LFM chirp, (b) an example of a chirp waveform in time domain

This signal arrives at a given pair of elements with different time delays, τ_1 and τ_2, corresponding to different transmission paths between the tag and the pair of elements. The two received signals are also attenuated to different extents, as follows

$$r_1(t) = a_1 \cos 2\pi[f_o(t-\tau_1) + (1/2)\mu(t-\tau_1)^2] \tag{5}$$

$$r_2(t) = a_2 \cos 2\pi[f_o(t-\tau_2) + (1/2)\mu(t-\tau_2)^2] \tag{6}$$

The signals are then de-ramped at the receiver,

$$d(t) = r_1(t) \cdot r_2(t) \tag{7}$$

Equation (7) will yield a lower frequency term and a higher frequency term but the higher frequency term will be rejected by the low-pass filter in the receiver. (Fig. 1(b)) Thus, the actual de-ramp output is

$$\begin{aligned} d(t) = a_1 a_2 \cos 2\pi[&f_o(\tau_2 - \tau_1) \\ &+ (1/2)\mu(\tau_1^2 - \tau_2^2) + \mu(\tau_2 - \tau_1)t] \end{aligned} \tag{8}$$

and has a much lower frequency indicative of the time delay,

$$f_d = \mu(\tau_2 - \tau_1) = \mu \cdot \Delta\tau \tag{9}$$

Measurement of this frequency therefore allows very straightforward calculation of the differential time delay and hence differential range, as follows

$$\Delta R = \frac{cT_c f_d}{B} \tag{10}$$

where c is the propagation velocity.

Normally the differential time delay is very small compared to the chirp duration. Therefore, the de-ramp pulse duration is slightly reduced as a result of the delay between the received signals, by a fractional amount $\Delta\tau / T_c$. The number of cycles of sinusoid present in the de-ramped output is

$$N_{cycles} = f_d T_c = B\Delta t = B \cdot \Delta R / c \tag{11}$$

According to (11), with the chirp bandwidth of 100MHz, one metre of differential range will result in 0.33 cycles of de-ramped sinusoid pulse, which confirms the need for a processing technique capable of accurately estimating the frequency of a short sample of sinusoid.

The de-ramped pulse may be processed using standard FFT techniques, giving a sinc response with a 3.9 dB width of 1/Tc, resulting in the classic range resolution limit of c/B. Consider the LFM-TDOA system illustrated in Table I, the corresponding range resolution limit is about 3.5 m.

IV. Experiment Settings and Results

The following experiments are based on a prototype active RFID location estimation system designed according to the methodology discussed in section II and section III. Table I illustrates the profile of this system.

The experiments include two components of work, aiming at showing the functionality and performance of the proposed LFM-TDOA scheme. The first set of experiments was performed through coaxial cable connections providing a low noise environment to demonstrate the time-difference measurement capability of the proposed method. The second set of experiments shows the performance of the LFM-TDOA method used in real world indoor environment.

TABLE I. System Profile

Parameter	Descriptions
Frequency	2.4GHz ISM band
Bandwidth	83.5MHz
Antenna units	Receive-only AU
Tag type	Transmission-only active tag
Modulation scheme	Linear frequency modulation
Chirp duration	1 us, 10 us, 80 us; (selectable)
Reading range	20 meters, line of sight (LOS) from reader;
Output power	5 dBm

A. *Functionality experiment*

The Fig. 4 shows the measurement settings and the range detector of the system described by Table I. In Fig. 4, there are two IF inputs that are down-converted from the wideband LFM chirps originating from a chirped RFID tag, through 50 dB attenuation. The upper IF channel passes to the de-ramp unit directly whereas the lower channel passes through a longer cable that provides a differential time delay for measurement.

The input IF signals are then processed in the de-ramp unit. In the de-ramp unit, there is an IQ mixer that produces two outputs in phase quadrature (Fig. 4) and allows polarity of the frequency estimator output to determine whether the time delay is leading or lagging.

The de-ramped output is sampled at 25MSps and the range estimation is performed in MATLAB, but can also be executed in real time using an FPGA. Fig. 5(b) shows the FFT result obtained from a measurement with a 6.1m differential path length. The FFT range estimator results in 6.1m range difference, which exactly equals to the transmission path difference induced by the delay cable.

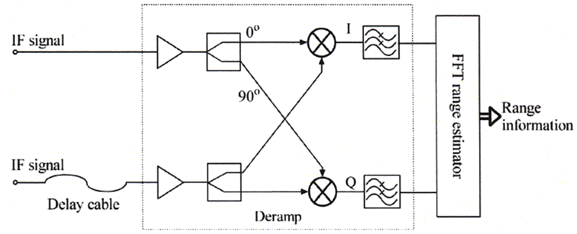
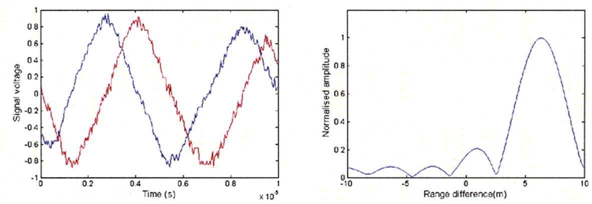


Figure 4. De-ramp process of the received LFM chirps



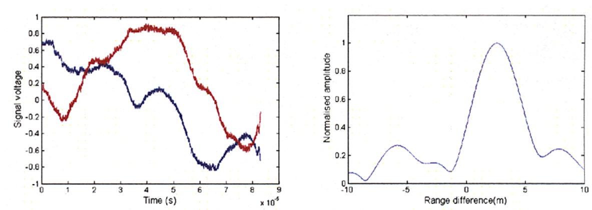
(a) (b)

Figure 5. (a) Normalized I and Q channel de-ramp outputs, chirp duration Tc=10us, swept bandwidth B=83MHz, (b) the according range estimation

B. *Experiments in indoor environment*

The second experiment examines the wireless path measurement ability of the LFM-TDOA scheme in a real indoor environment. The same setting as in Fig. 4 is used to estimate range difference. In contrast to experiment A, the input signals in this experiment come through air channel from a radiated chirped RFID tag, rather than through a cable connection.

Again, the de-ramped output is sampled at 25MSps rate. Fig. 6(a) and Fig. 6(b) respectively show the time domain and frequency domain results from a measurement case where the real propagation path difference is 2.81m.



(a) (b)

Figure 6. (a) Normalized I and Q channel de-ramp outputs, chirp duration Tc=80us, swept bandwidth B=83MHz, (b) the according range estimation

Compared to the results shown in Fig. 5, the time domain signals in Fig. 6(a) experience much more additional noise. This is evident from the close-in noise level in Fig. 5(b) and Fig. 6(b). The range difference estimated from this experiment is 2.55m, 0.26m smaller than the real path difference. This error is due to the ambiguities introduced by the air channel, such as noise and in-band interference.

To show statistical performance of the LFM-TDOA scheme, the same experiment is repeated under identical measurement settings, and the statistics data from these results are shown in Fig. 7 and Fig. 8. It is worth to point out, higher range accuracy can be achieved by applying more sophisticated processing techniques, such as segmented chirp frequency estimation, which assists to identify and avoid narrow band burst interference.

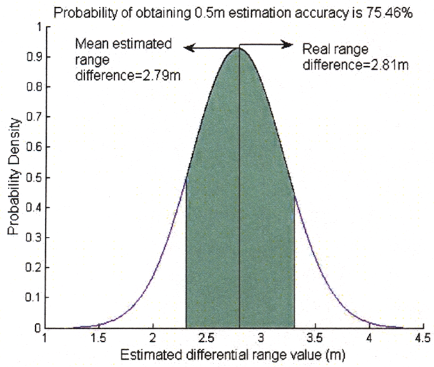


Figure 7. Probability density distribution of the statistics of a case done in indoor environent, with 2.81 real range difference

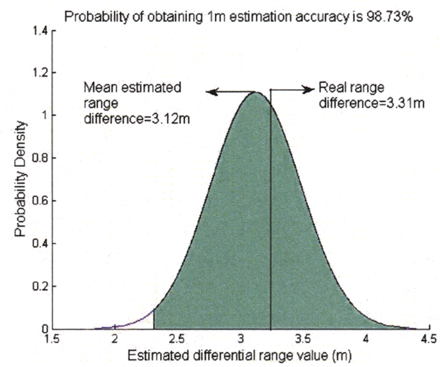


Figure 8. Probability density distribution of the statistics of a case done in indoor environment, with 3.31 real range difference

The results indicate that the proposed basic LFM-TDOA scheme provides precision of about 0.5 m with probability of about 75%, (Fig. 7) and the probability for obtaining 1 m range estimation accuracy is about 99%. (Fig. 8)

V. Discussion and Conclusion

This paper introduces a new design of indoor positioning system based on the use of a linear FM chirp tag signal and full-deramp receiver processing. The ranging mechanism described in this paper was developed for applications require compact tag designs. It is achieved by using listen-only receiver network, which makes for a simpler realization based on TDOA estimation. Alternatively, a matched filter receiver using dispersive delay line is required, although DDL is more complicated in terms of implementation. [9]

To optimize the proposed LFM-TDOA method, a few more factors are worthwhile to consider.

In this paper, the proposed method is demonstrated in a 2.4 GHz system but this methodology is not limited to this band. A wider sweep bandwidth would allow greater location estimation precision.

The experiments were performed in a Wi-Fi coverage area, resulting in quite significant interference. Attention may also need to be paid to other radio services such as Bluetooth or digital TV that may produce additional interference.

This paper also mentions the benefit of using more than three antenna units to monitor one cell. (Section II) The additional receiver provides an additional candidate hyperboloid to uniquely define the location in 3 dimensions. A further benefit is that the additional hyperboloid can also be used to determine if NLOS occurs. With this information, it is possible to evaluate the confidence level of a result location determined.

With careful consideration and design, further optimization such as that described above should enable the LFM-TDOA technique described here to provide a simple but high performance location technique for indoor applications.

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