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A Mitigation of Multipath Ranging Error Using Non-linear Chirp Signal

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Abstract – While the chirp signal is extensively used in radar and sonar systems for target decision in wireless communication systems, it has not been widely used for positioning in indoor environments. Recently, the IEEE 802.15.4a standard has adopted the chirp spread spectrum (CSS) as an underlying technique for low-power and low-complexity precise localization. Chirp signal based ranging solutions have been established and deployed but their ranging performance has not been analyzed in multipath environments. This paper presents a ranging performance analysis of a chirp signal and suggests a method to suppress multipath error by using a type of non-linear chirp signal. Multipath ranging performance is evaluated using a conventional linear chirp signal and the proposed non-linear chirp signal. We verify the feasibility of both methods using two-ray multipath model simulation. Our results demonstrate that the proposed non-linear chirp signal can successfully suppress the multipath error.

Keywords: CSS(Chirp Spread Spectrum), Non-linear chirp signal, Multipath, Two-ray multipath model

1. Introduction

Nowadays, location based services (LBS) are a topical subject in the field of mobile communications [1]. GPS is the most widely used location system, as it provides a position measurement with sufficient accuracy, and a wide coverage area, with stable transmission signals.

However, due to the essential characteristic of GPS signals, many problems arise when used in dense urban and indoor environments. In urban areas, the many buildings decrease the visible satellites and reflect the GPS signal, causing a multipath problem [2-4]. This is the main problem with GPS navigation systems that needs to be resolved for the mobile user. Furthermore, the GPS signal is often too weak to be received in an indoor environment.

In order to compensate for these GPS limitations in outdoor and indoor environments, many positioning methods have been proposed, using systems such as wireless local area networks (Wi-Fi), ultrasonic waves, cellular communication systems, and DTV sync signals with a time-of-arrival (TOA) scheme [5-10].

Due to the increasing demand for indoor positioning, a range device for the IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for Wireless Personal Area Networks (WPANs) has been defined in the IEEE 802.15.4a standard. In the standard Ultra Wide Band signal (UWB), the Chirp Spread Spectrum (CSS) is chosen for the Physical Layer (PHY) [11-13].

However, pulsed UWB using an extremely short time duration of time pulses with an extremely high peak-to-average ratio causes many hardware implementation problems [14]. One of these problems is the power amplifier nonlinearity when the system is designed to operate at low data rates but with a large frequency bandwidth. Another problem is that it also requires an extremely fast power rise time and low-noise amplifiers (LNA), which currently incur high costs [15]. Chirp signal schemes have historically been used extensively in radar systems for target detection [16-17]. Compared with pulsed UWB schemes, the chirp schemes can overcome their shortcomings. Using a long time duration modulation waveform without a high peak-to-average ratio, power amplifier nonlinearity in the system can be avoided. Low-cost and low-complexity hardware can be used in the LNA parts of an apparatus. The chirp signal is robust against multipath fading due to its inherent signal structure. Therefore, applying a chirp pulse signal in positioning systems is a new way to increase location accuracy.

The recent research of communication system uses the non-linear modulated chirp signal instead of using only the linear modulated chirp signal. The communication system using the non-linear chirp signal performs better than the conventional communication and interference suppression schemes because it can increase the data transmission rate and decrease interference at the same time [18-19]. Therefore, the non-linear chirp signal has been a widely

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used communication system to improve the bit error rate (BER) performance [20-21]. However, this paper proposes a new non-linear chirp signal modulation system for navigation systems. This is first the study that analyzes a multipath ranging performance using the non-linear chirp signal. Using the proposed non-linear chirp signal scheme, system performance under the multipath condition is improved compared with conventional linear chirp systems. The design of this multipath resistible non-linear chirp is described. The system performance, especially the ranging error of conventional linear chirps and the proposed non-linear chirps are compared using computer simulation. The simulation results confirm that the proposed scheme outperforms the traditional linear chirp schemes. Our preliminary study shows that the suggested chirp signal is an excellent candidate for a precise navigation system.

2. Basics and Design of Chirp Property

2.1 IEEE 802.15.4a standard

Short-range wireless network applications are very popular nowadays as they can provide high speed communications and precise ranging, as well as ultra low power, low complexity and low cost. The IEEE 802.15.4a standard was introduced to meet the growing need for such applications. The standard consists of two optional PHYs: the UWB Impulse Radio (operating in a 3.1 GHz - 10.6 GHz spectrum) and the Chirp Spread Spectrum. It is the first international standard that specifies a wireless PHY to enable precision ranging. However, ranging is supported only by UWB, and CSS is only used for data communications despite its potential capacities.

2.2 Linear chirp signals

Chirps are sinusoidal signals of which the frequency varies with time. Depending on the type of chirp, the frequency variation is linear. Chirp signals have been extensively used in radar and sonar systems to determine, among other characteristics, the range, velocity, and angular position of a target object. The representation of a linear chirp signal $y(t)$ is defined in Eq. (1)

$$y(t) = cos\left[\Omega(t)\right] \tag{1}$$

$$\Omega(t) = 2\pi f_s t + \pi\mu t^2 \tag{2}$$

$$\mu(t) = \frac{f_{BW}}{2 \cdot T_s} \tag{3}$$

where f_s is the center frequency and $\Omega(t)$ is the phase function. Fig. 1 shows how the chirp signal changes in frequency with time. Eq. (3) gives the sweep rate $\mu(t)$ of the signal in terms of the chirp duration T_s and chirp bandwidth f_{BW} . The instantaneous frequency of $f_c(t)$ is defined as

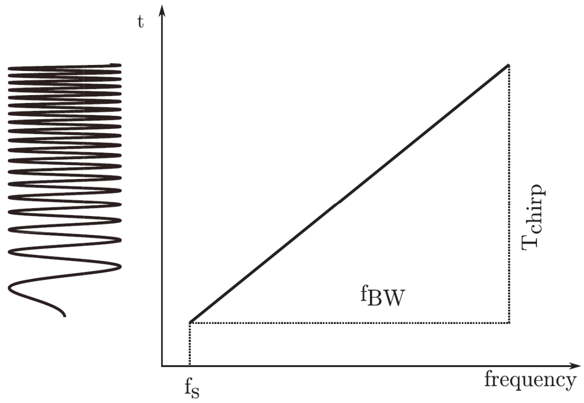

Fig. 1. Frequency and time relationship of chirp signal

$$f_c(t) = \frac{1}{2\pi}\frac{d\Omega(t)}{dt} \tag{4}$$

$$f_c(t) = f_s + \mu \cdot t \tag{5}$$

The chirp rate, an important parameter in the chirp system, is defined by

$$\mu(t) = \frac{df_c(t)}{dt} = \frac{1}{2\pi}\frac{d^2\Omega(t)}{dt^2} \tag{6}$$

$$\mu(t) = \frac{df(t)}{dt} = \mu \tag{7}$$

It represents the rate of change of the instantaneous frequency. The chirp waveforms with $\mu(t) > 0$ are called up-chirps and those with $\mu(t) < 0$ are called down-chirps.

Due to the linear frequency sweep, chirp signals can be efficiently compressed into pulses referred to as pulse compression. This is achieved by correlating the received chirp signal with its matched filter. If we take the waveform to be centered at t =0, it can be written as

$$y(t) = cos\left[2\pi f_s t + \pi\mu t^2\right] \tag{8}$$

$$f_{BW} = |\mu| \cdot T_s \tag{9}$$

The impulse response of a matched filter for a linear chirp signal is also a linear chirp signal but with a chirp rate of the opposite sign. If a chirp waveform is fed into its matched filter the output signal typically has a narrow IF peak at the chirp center frequency. If we consider chirp waveforms with flat time domain envelopes and take the matched filter to be centered at t =0, we find an analytical expression for the output waveform $g(t)$ of the matched filter as follows [18]

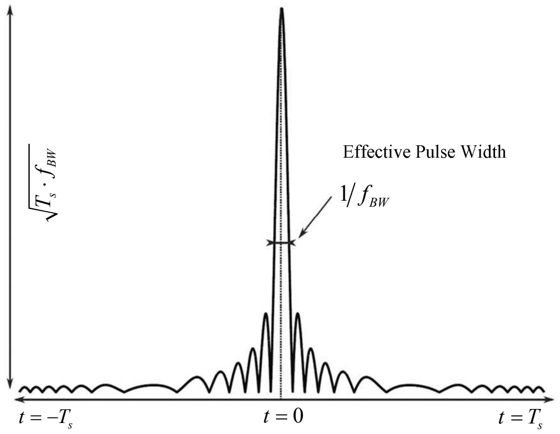

Fig. 2. Chirp signal output of matched filter

$$\begin{aligned} g(t) &= h(t) * y(t) \\ &= y^*(-t) * y(t) \\ &= \sqrt{f_{BW} T_s}\, \frac{sin[\pi f_{BW} t(1-\frac{|t|}{T_s})]}{\pi f_{BW} t} cos(2\pi f_s t) \end{aligned} \tag{10}$$

for $-T_s < t < T_s$. The envelope has its maximum at t =0, and its first zeros at $t \approx \pm 1/f_{BW}$. The pulse width of the chirp T_s is compressed to an effective width of $1/f_{BW}$. The ratio of the input and output pulse widths is therefore given by the time bandwidth product $T \cdot f_B$, which is known as the compression ratio or processing gains. The matched filter output with a chirp input is a short pulse as shown in Fig. 2. The effective output of the matched filter is the combined energy of the chirp pulse over its entire duration. This results in a processing gain that increases the signal-to-noise ratio at the receiver, thus reducing the bit error rate. Chirp pulse compression combines high processing gain with the improved distance resolution of short pulses.

The use of chirp signals provides several advantages. Chirp signals exhibit high effective bandwidth as they sweep through the entire frequency space. Due to the larger bandwidth, they are less susceptible to multipath and other channel disturbances. In addition, the strong auto-correlation properties of the chirp signals add more robustness to distance measurements in multipath environments.

2.3 Proposed nonlinear chirp signals

As mentioned in the previous section, when $\mu(t)$ is a constant value, we consider this to be a type of linear chirp signal. "Linear chirp" means that all frequency sections in the frequency bands have the same weights, thus in the receiver matched filter, the sweeping frequency bands will be treated the same.

Based on this principle, we propose a non-linear chirp waveform. Unlike the linear chirp waveform, the non-linear chirp waveform is defined as a chirp function of which the chirp rate $\mu(t)$ is not a constant value but a variable function of time t. In this paper, we use a sinusoidal curve of chirp rate because it has many advantages such as good non-linear properties and ease of hardware implementation. In the proposed scheme, we consider the instantaneous frequency to pass the central frequency with the highest velocity. Thus, the proposed scheme can suppress a multipath effect.

The instantaneous frequency and phase function of a non-linear chirp are given by

$$f_c(t) = f_i + a \cdot cos(b \cdot t) \tag{11}$$

$$\Omega(t) = 2\pi f_i t + 2\pi a \cdot sin(b \cdot t)/b \tag{12}$$

where parameters a and b adjust the chirp waveform and f_i is the central frequency of the proposed non-linear chirp signal. The proposed non-linear chirp signal and chirp rate are respectively defined by

$$y(t) = cos(2\pi f_i t + 2\pi a \cdot sin(b \cdot t)/b) \tag{13}$$

$$\mu(t) = -a \cdot b \cdot sin(b \cdot t) \tag{14}$$

The linear and non-linear chirp signal instantaneous frequency $f_c(t)$ comparisons are shown in Fig. 4. For the non-linear chirp, the maximum multipath suppression can be achieved at the instant when the absolute value of $\mu(t)$ reaches its maximum value, that is,

$$t_0 = \arg\max_t |\mu(t)| \tag{15}$$

We adjust $f_c(t_0)$ to the central frequency of the proposed non-linear chirp signal, which means $f_c(t_0) = f_i$ =5GHz. In the proposed design, f_{high} =10.6GHz, f_{low} =3.1 GHz, and $f_m = (f_{high} + f_{low})/2$ are the highest, lowest, and central frequencies of the UWB spectrum band, respectively. A non-linear chirp curve with a phase range of π and a center frequency of f_i is adopted. To utilize the entire spectrum band, at least one of the two edge frequencies of the curve should be f_{high} or f_{low} . If f_i is not equal to f_m , the frequency range of the entire curve exceeds the UWB spectrum band. We truncate the curve to cover the frequency scope of 3.1 GHz to 10.6 GHz. Therefore, only the upper half and about one third of the lower half of the non-linear chirp curve can be utilized. Parameters a and b can be generalized as follows:

$$\left.\begin{aligned} a &= f_{high} - f_i \\ b &= \frac{1}{T_s} arcos\left(\frac{(f_{low} - f_i)}{(f_{high} - f_i)}\right) \end{aligned}\right\} if\ f_i \le f_m$$
$$\left.\begin{aligned} a &= f_{high} - f_i \\ b &= \frac{1}{T_s} arcos\left(\frac{(f_{high} - f_i)}{(f_{low} - f_i)}\right) \end{aligned}\right\} if\ f_i > f_m \tag{16}$$

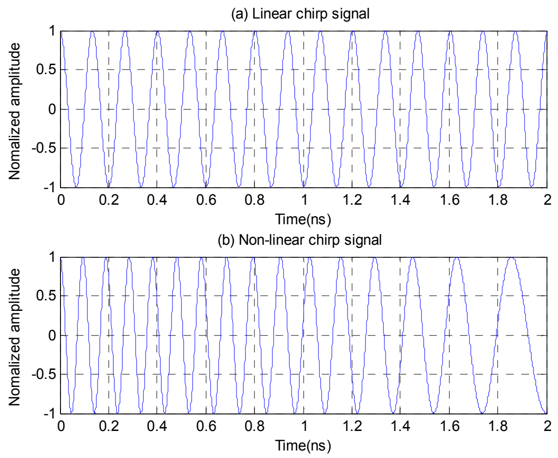

Fig. 3. Comparison of linear chirp signal and proposed non-linear chirp signal

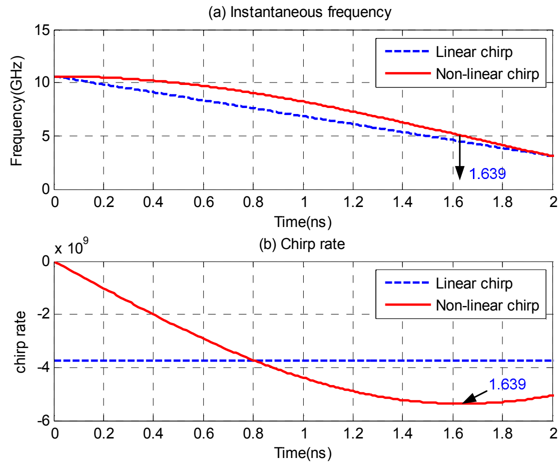

Fig. 5. Chirp rate of linear and non-linear chirp signal

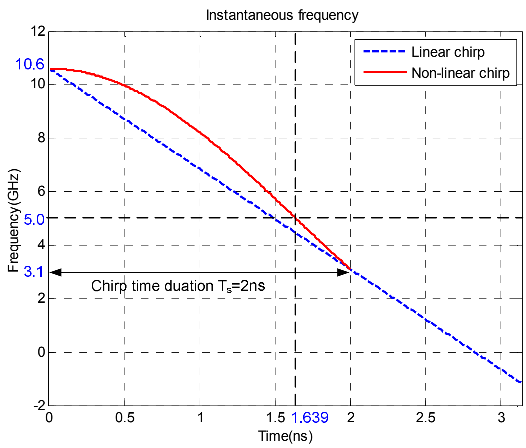

Fig. 4. Time-frequency relationship of non-linear chirp

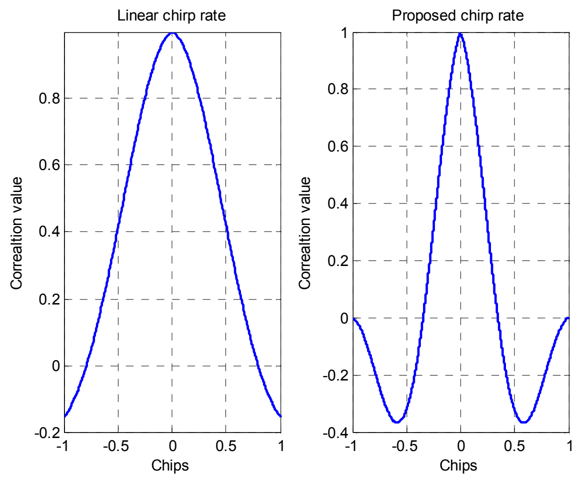

Fig. 6. Result of matched filter output according to chirp rate

Fig. 3 shows the traditional linear chirp signal and our proposed non-linear chirp signal. The proposed waveform is designed according to the method above. A center frequency of designed the non-linear chirp signal is 5.0GHz, which is equal to the design parameter f_c in Eq. (11).

The proposed method is plotted in Fig. 4. We use a sinusoidal curve as the instantaneous frequency function of the non-linear curve. At the point where the absolute value of chirp rate $\mu(t)$ reaches maximum value, the instantaneous frequency should be the central frequency; at this point, the slope of the non-linear curve is the maximum value. This means that in the output signals of the receiver correlator, the multipath effect has a minimal effect on system performance.

Fig. 5 shows that, for the central frequency of 5.0 GHz, only two-thirds of the sinusoidal curve can be used. The zero crossing point is set at $f = f_i$ =5.0 GHz. The instantaneous frequency and chirp rate of the two chirps are given in Fig. 5. At the corresponding time point of zero crossing in the instantaneous frequency (t = 1.639 ns), the chirp rate of the proposed chirp achieves the minimum value. This also confirms that the proposed non-linear chirp passes the central frequency with the maximum speed and will achieve the best multipath suppressing performance in the receiver.

Because of the multipath propagation, the spectrum of the received signal is extended towards lower frequencies. The direct-path signal mainly influences the higher frequency components of the observed spectrum, while the multipath component affects part of the spectrum at lower frequencies. It is therefore recommended that the high value of the chirp rate μ is used for multipath error mitigation [22].

A high value of the non-linear chirp rate μ means that in the chirp signal, the frequency which matches the multipath error occupies the minimum time duration. This means that in the output of the matched filter Eq. (10), the sidelobe of the matched filter output is reduced and the shape of the correlation peak value is sharpened. It also means that the proposed non-linear chirp signal performs a role similar to that of a narrow-correlator [23]. The result of the matched filter output according to chirp rate is depicted in Fig. 6. This confirms that the proposed chirp signal improve the ranging resolution.

3. Evaluation of Multipath Performance

3.1 Multipath

A useful position for a user is acquired by examining the autocorrelation and arrival time if there is no channel interference or delay in the location system. However, in reality, a transmitted signal is distorted and delayed due to various obstacles and reflections on its way to a receiver. While a signal passing through a single path of a line-of-sight is ideal, it passes through multiple paths due to reflections between buildings and walls. This is called a multipath problem and causes an asymmetrical, deformed autocorrelation function.

3.2 Two-ray model

In this paper the two-ray model will be considered. The two-ray multipath model is not realistic but they provide useful diagnostic insights. It is also used to understand how the multipath affects the tracking loops. Further, two-ray model is sufficient, to perform well under simple multipath conditions. Therefore, the two-ray multipath model has been a widely used to evaluate the multipath ranging error analysis [4, 19, 24-25]. The simplest way to represent a multipath problem is the two-ray model depicted in Fig. 7 where a transmitted signal reaches a receiver in two paths, one through a direct path and the other through a reflected path that is τ second longer. The transfer function representing the path characteristics may be expressed in impulse response as follows

$$h(t) = \delta(t) + \alpha \exp(j\theta\pi/180)\delta(t-\tau) \qquad (17)$$

where α and θ represent the relative magnitude and phase of the second path, respectively, and τ is the time delay of the second path relative to the direct path.

Without the multipath, the autocorrelation of the CSS system is symmetric, as shown in Fig. 6. However, the symmetry does not hold if a signal is delivered with the multipath similarly to the two-ray model. Fig. 8 shows the autocorrelation and its asymmetry function in the case of α =0.5, θ=0 deg and τ =0.24ns in Eq. (17). An asymmetric autocorrelation and symmetric function result are plotted in Fig. 8. An asymmetric autocorrelation is plotted on the left-hand side while the following function value is plotted on the right-hand side

$$s(t') = c(t'-0.5) - c(t'+0.5) \qquad (18)$$

where $c(t')$ is a correlation value t' plotted on the left-hand side of the figure. Therefore, $s(t')$ represents a difference in the autocorrelation value of one chip length between $(t'-0.5)$ and $(t'+0.5)$. t' varies from -1 to 1. For instance, if $t' = -0.5$, then $c(t'-0.5) = c(-1) = 1\times 10^{-5}$, $c(t'+0.5) = c(0) = 3.25 \times 10^{-5}$, and therefore $s(t') = -2.25\times 10^{-5}$. We can find a correlation error due to multipath by solving $s(t')=0$ for t'. In Fig 8 which represents the case of $\tau = 0.5$ chip, $s(t')=0$ if t' = 0.135chip. That is, the correlation error is 0.135 chip if there is a multipath delay of 0.24ns. The correlation error of 0.135 chip is equivalent to 2.30 m in position error.

The correlation ranging errors due to varying multipath delay τ in the conventional linear chirp signal, as described in Fig. 6, are plotted in Fig. 9. The upper part of the figure represents the case of α =0.5 and θ=0 deg and the lower part represents the case of α =0.5 and θ=180 deg. For the conventional linear chirp, the positive

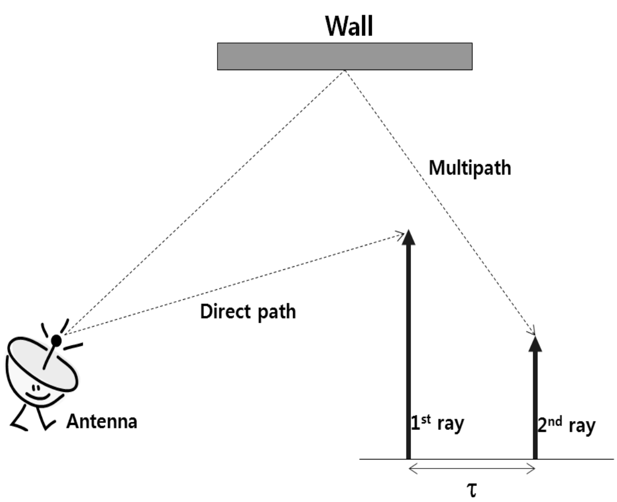

Fig. 7. Two-ray multipath model

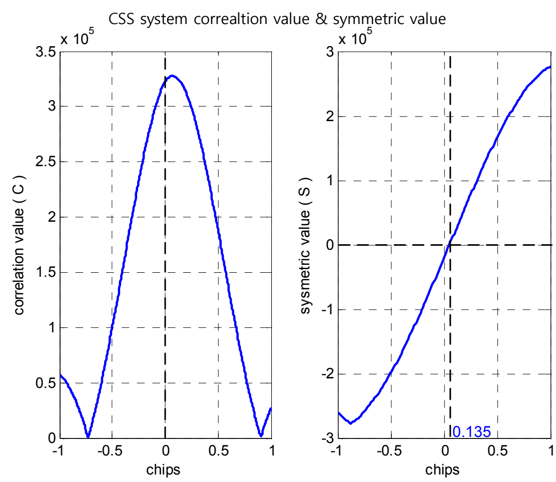

Fig. 8. Autocorrelation value and symmetric value of chirp signal

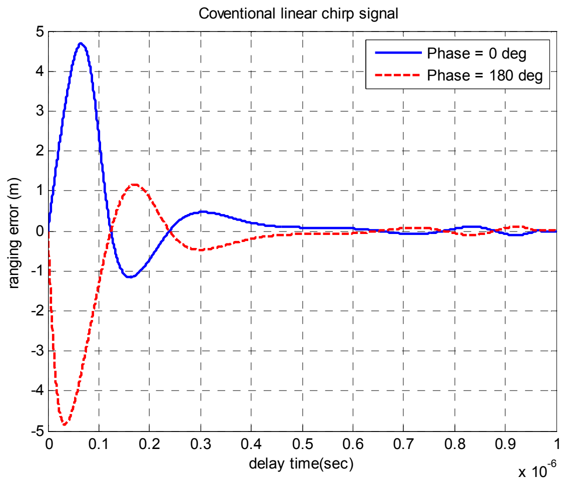

Fig. 9. Multipath ranging error of conventional linear chirp signal

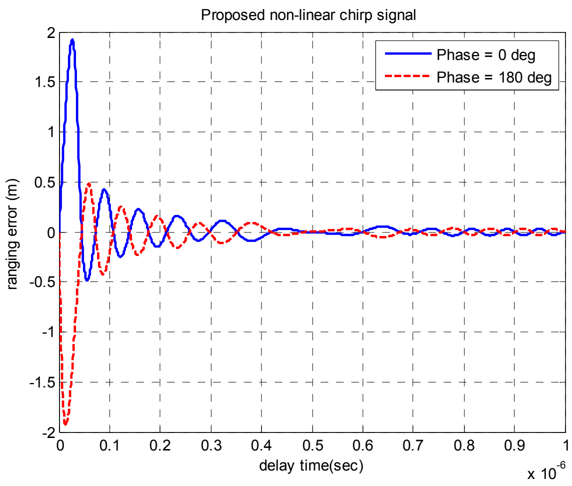

Fig. 10. Multipath ranging error of proposed non-linear chirp signal

maximum ranging error is 4.68m at τ=0.065usec and the negative maximum ranging error is -4.83m at τ=0.034usec.

The effect of the multipath on the proposed chirp signal is similarly studied by investigating the correlation ranging errors. The correlation ranging errors by varying multipath delay τ in the proposed non-linear chirp signal are plotted in Fig. 10. Similarly to the linear chirp case, the upper part of the figure represents the case of α=0.5 and θ=0 deg and the lower part represents the case of α=0.5 and θ=180 deg. The correlation ranging error has a maximum value of about ±1.9m at τ=0.026 and τ= 0.013usec.

Our ranging performance simulation was performed for the conventional linear chirp signal, the ultra wide band (UWB) signal and the proposed non-linear chirp signal. As previously mentioned, for all the simulations we assumed a two-ray multipath model in the system. The system performance (ranging error) of the conventional linear

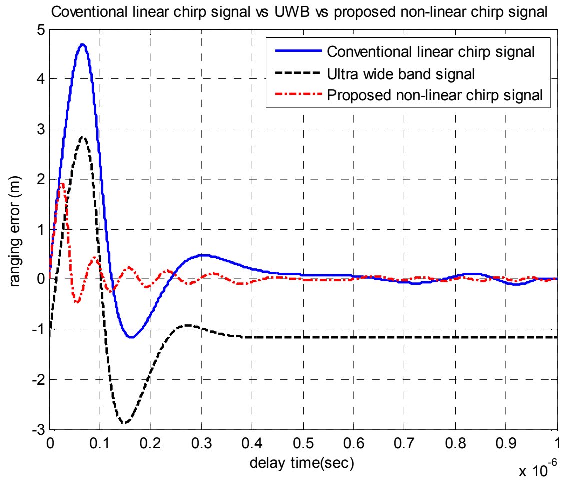

Fig. 11. Ranging performance of linear chirp, UWB and proposed chirp signal.

chirp, UWB and the proposed non-linear chirp are compared in Fig. 11 with different delay time values. The results show that the proposed non-linear chirp system has a better performance than the other signals.

4. Conclusion

The wide band radio location is currently one of the most promising technologies for accurate localization systems. However, the multipath is main error source in the location system. Multipath can cause serious problem for precision position estimation.

In this paper, we analyze a chirp spread spectrum ranging system based on a chirp signal with the ability of multipath error suppression. In order to reduce the multipath error effect, a non-linear chirp signal is proposed and its ranging performance is evaluated by computer simulation. The results verify that the proposed non-linear chirp signal can successfully suppress the multipath ranging error to a certain degree compared with the other traditional signals. The proposed method can be utilized as an accurate navigation system.

Acknowledgements

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