Improved Method for TDOA Estimation with Chirp Signals

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This paper introduces an improved method for TDOA estimation. The time-difference measurement is performed by taking an advantage of the properties of linear frequency modulation signals. According to the performed simulations and experiment results, the proposed TDOA estimation scheme shows good accuracy and thus has the potential to be used in precise indoor location applications.

Keywords and phrases: location, chirp, TDOA estimation.

Introduction

The interest in the indoor location systems has been growing recently due to the development of the real time location applications. Various solutions enabling objects location in different environments are presented in the literature [1, 2]. The most common technique used in such systems is TOA/TDOA (Time Of Arrival / Time Difference Of Arrival). Typically a few transmitting/receiving antennas are being used and based on the time or time difference of arrival, the location of the object is determined. Unfortunately detection of the signal arrival time is influenced by an error which causes an inaccuracy in determination of the object location. In the publications we can find many methods of minimizing such errors by applying different kinds of signals and different methods of detection [1, 3].

An interesting approach seems to be usage in the indoor location systems chirp signals. The advantages of such signals are their wide bandwidth, simplicity of the transmitting and receiving circuits and immunity to the narrowband interference. In the literature we can find many descriptions of such implementations [3–6]. In this paper author proposes a new approach which aims to increase the precision of objects location in indoor environments.

Location system concept

The system consists of a few transmitters (three in the basic case) which locations are known and receivers, which positions have to be calculated. It is also possible to implement an alternative solution in which the locations of transmitters are calculated based on the signals received by a few receivers with defined locations.

In the analyzed system the antennas emit successively signals which reach the receiver after a propagation time. Due to the intentional delays of the specific antennas emissions, overlapping of the received signals is disabled. Such system architecture requires time synchronization between transmitters. However the synchronization between receivers and transmitters is not required. The receiver's location is calculated based on the TDOA technique. The sequence of the signals emitted and received is presented in Fig. 1.

Triggers delays are expressed as t_{1del}, t_{2del}, t_{3del} and the propagation difference times as t_{12}, t_{13} and t_{13}.

Radio channel

One of the most problematic issues in the indoor positioning seems to be multipath propagation. Apart from the LOS path signal also multipath components are received which complicates precise determination of the signal arrival time and therefore the location of the

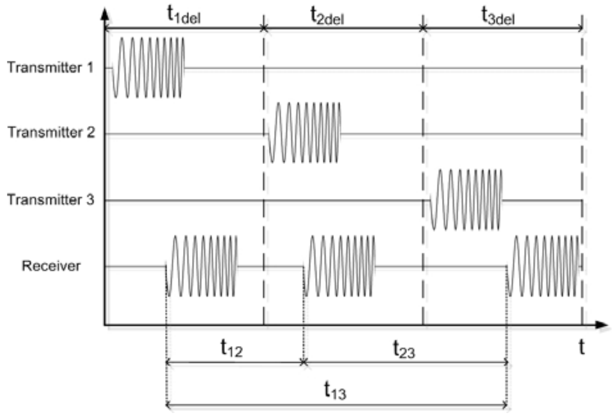

Fig. 1. Illustration of the signals emitted and received in the location system.

object cannot be accurately calculated. In this papers author focuses on the chirp signals, which instantaneous frequency varies linearly with time and can be expressed as [3]:

$$f(t) = f_0 + \mu t \qquad for\ 0 \le t \le T \tag{1}$$

where f_0 is the transmitted signal frequency at time t = 0 and μ is the chirp rate defined by:

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

where T_c is a chirp duration and B is a swept-frequency bandwidth. Thus, the transmitted signal can be expressed as:

$$y_t(t) = \cos 2\pi [f_0 t + (1/2)\mu t^2] \tag{3}$$

Depending on the sign of the coefficient μ we can call it “up chirp” or a “down chirp” signal [7].

In the signal received in the indoor environment we can also observe fading due to the multipath propagation. An exemplary signal is presented in Fig. 2.

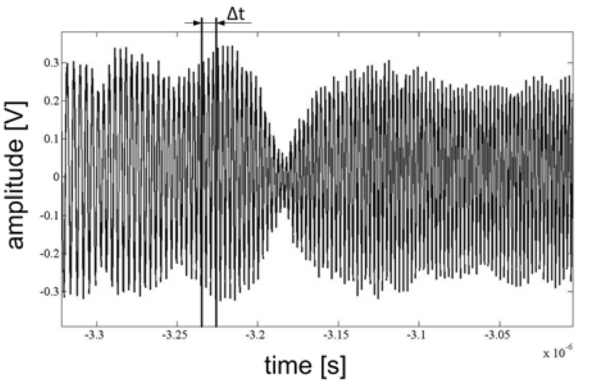

Fig. 2. Exemplary chirp signal received in the indoor environment.

Let’s consider “up chirp” signal y(t) in the two path propagation model [5] and its spectrum in the specific time window Δt as showed in Fig. 2. As the signal consists of LOS path and multipath component we can also expect those components in the spectrum as showed in Fig. 3. The solid line represents the spectrum of the y signal, while the dash and the dot lines — LOS path component and reflected chirp component respectively. Because the multipath component is delayed comparing to the LOS path, its frequency is lower (we would observe higher frequency if we consider “down chirp” signal).

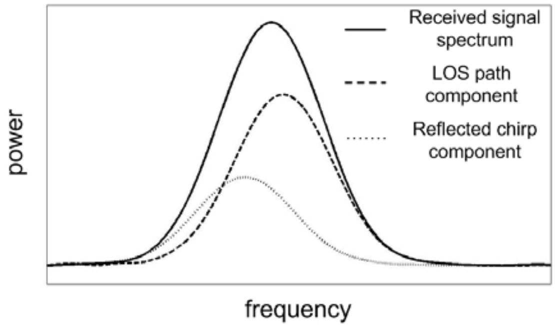

Fig. 3. Spectrum of the received signal, LOS path component and reflected chirp component.

Therefore the spectrum of the received signal y(t) was moved towards lower frequencies. Regarding those observations we can notice that the more separated multipath components in the frequency domain, the smaller error of the LOS component determination. So it is recommended to use high value of the coefficient μ for the generated signals. However it has to be noted that the coefficient μ is limited by the physical capabilities of the transmitting and receiving circuits. The value of the coefficient μ is also limited by the frequency and time period ranges corresponding to the chirp signal.

The proposed method of TDOA estimation

For the chirp signal we can determine Short-Time Fourier Transform (STFT) known also as a windowed Fourier transform [8, 9]. The STFT is a linear time-frequency representation. Since the duration of the window is small, it is possible to monitor the local frequency spectrum. Through the translation of the window in time domain, the STFT describes how the signal frequency spectrum varies as a function of time. The ridges of the STFT are defined as the set of local maximum of the modulus of the STFT in the time-frequency plane. In the case of frequency of the modulated signals, it is proved that ridges are distributed along instantaneous frequency of the signals (this method of instantaneous frequency calculation was denoted as M_1). The energy of the signal concentrates around ridges and therefore the ridges of the STFT contain crucial information on the characteristics of the signal [9].

Because of the multipath components, the most part of the STFT ridge of the received signal is delayed (moved towards lower frequencies) as illustrated in Fig. 4.

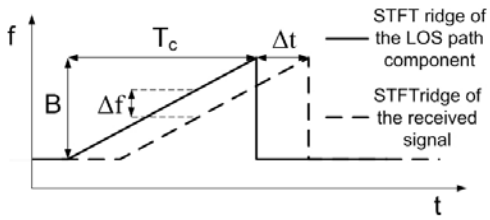

Fig. 4. Influence of the multipath propagation on the STFT ridge.

Therefore author proposes an additional method of the instantaneous frequency calculation based on the STFT ridge. Let's assume that $y_0(t)$ is a generated chirp signal of a length t (starting in t_{start} and lasting till t_{stop}) and y(t) is a received signal. We calculate $stft_0$ as described by method M_1. Author proposes an additional method to calculate the instantaneous frequency based on STFT ridge (f_{STFT}) as described below (method M_2). Please notice that the notation x: f(x)=y means to find such value of x that f(x) equals y.

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For $\Delta t \in (t_{start}, t_{stop})$:
  1. $s_0=fft(y_0)$ for the specific time window $\Delta t$
  2. $s_{0max}=max(s_0)$
  3. $s=fft(y)$ for the specific time window $\Delta t$
  4. $s_{max}=max(s)$
  5. $k_{norm}=s_{max}/s_{0max}$
  6. $s_{0norm}=s_0/k_{norm}$
  7. $s_{0norm\_max}=max(s_{0norm})$
  8. $f_{0max}$: $s_{0norm}(f_{0max})=s_{0norm\_max}$
  9. $f_{0dmax}$: $s_{0norm}(f_{0dmax})=s_{0norm\_max}/2$ and $f_{0dmax}>f_{0max}$
 10. $f_{delta}=f_{0dmax}-f_{0max}$
 11. $f_d$: $s(f_d)=s_{max}/2$. As more than one $f_d$ exist — the
     maximum value should be chosen
 12. $f_{STFT} = f_d-f_{delta}$
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Let's express the instantaneous frequency f_{STFT} in the time function as $stft_{1b}$. In order to estimate TDOA, above calculations should be performed for the signals received from the pair of antennas and the correlation between calculated STFT waveforms should be performed as follows. Please note, that the correlation(x,y) means finding the correlation of template x within y waveform and index 2 refers to the signal emitted by the second antenna.

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 1. $cor_{10a}=correlation(stft_0,stft_{1a})$
 2. $cor_{10b}=correlation(stft_0,stft_{1b})$
 3. $cor_{20a}=correlation(stft_0,stft_{2a})$
 4. $cor_{20b}=correlation(stft_0,stft_{2b})$
 5. $t_{1a}$: $cor_{10a}(t_{1a})=max$
 6. $t_{1b}$: $cor_{10b}(t_{1b})=max$
 7. $t_{2a}$: $cor_{20a}(t_{2a})=max$
 8. $t_{2b}$: $cor_{20b}(t_{2b})=max$
 9. $TDOA_{M1}=t_{2a}-t_{1a}$                       ($M_1$ method)
10. $TDOA_{M2}=t_{2b}-t_{2b}$                       ($M_2$ method)
11. $TDOA_{M3}=(TDOA_{M1}+TDOA_{M2})/2$             ($M_3$ method)
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As a result of the proposed algorithm three TDOA estimates for the pair of emitting antennas are calculated ($TDOA_{M1}$, $TDOA_{M2}$ and $TDOA_{M3}$).

Simulations

The aim of the simulations was to study the influence of the radio channel on the TDOA estimate error with the algorithm proposed by the author. To support the simulations a dedicated application in Matlab environment was developed. The tool enabled simulation of the Saleh-Valenzuela (SV) propagation models (CM1-CM4) [10]. Table 1 illustrates the values of the parameters used in the simulations.

Table 1. Values of the simulations parameters.

Output power	3 dBm (316 mV)
Bandwidth	100–300 MHz
Modulation scheme	Linear frequency modulation
Chirp duration	2–10 μs
Chirp rate range	10^{14}–10^{18} Hz/s
SV model	CM1
Sampling frequency	2 Gs/s
Fourier window type	Hamming
Fourier window length	120 samples

Due to the performed simulations it was possible to calculate TDOA errors for different range of parameters. Regarding the limitation of the hardware, the chirp rate range (μ) between 10^{14} and 10^{16} Hz/s was studied. The simulations concerned SV model which represents multipath propagation environment. As the system was planned to be used within LOS environment, CM1 model was studied. In the Fig. 5 the dependency between the TDOA estimates standard deviation and the coefficient μ is presented for the three algorithms: M_1, M_2 and M_3, as described in Section 3.

As it can be seen the higher value of the coefficient μ the lower deviation can be observed. This is due to the fact that for the higher values of the coefficient μ there is bigger separation between the LOS and multipath components. Additionally it was noticed that algorithm M_3 resulted in the lowest deviation while M_1 in the highest one. Therefore it was decided to perform experimental measurements to verify better accuracy of M_3 algorithm in the real environment.

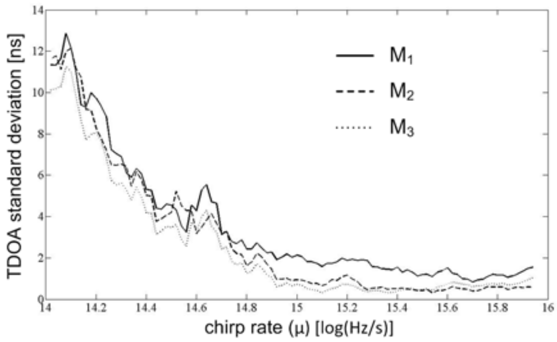

Fig. 5. TDOA estimates standard deviation as a function of chirp rate.

Measurements

The block diagram of the measurement setup is presented in Fig. 6.

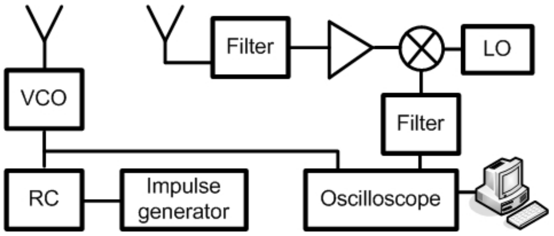

Fig. 6. The block diagram of the measurement setup.

A simple RC circuit was used for VCO tuning signal generation. The generated signal was not linear as assumed in Section 2, however it doesn't influence the TDOA estimations. The specification of the signal and equipment parameters are shown in Table 2.

Table 2. Signal and equipment parameters.

Chirp duration	3,5 us
Mean chirp rate (μ)	$1,58*10^{15}$ Hz/s
Signal frequency range	3,973–4,388 GHz
Heterodyne frequency (LO)	3,95 GHz; 13 dBm
Signal frequency range after conversion	23–438 MHz
Sampling frequency	2 Gs/s

The developed application enabled recording of the received signal and supported TDOA estimations according to the algorithms proposed by the author.

During the measurement campaign both antennas were located on the tripods on the same level. The distance between antennas ranged from 0,5 m to 4,5 m. It was decided to use in the measurements only one transmitting and one receiving antenna and use trigger signal as a time reference. Such approach made the measurement easier to be performed, but didn't influence the results of the studies. The results of the measurements were used to estimate TDOA. For each pair of signals TDOA was calculated with the algorithms described in Section 3. The best results were obtained with M_3 algorithm and the worst ones with M_1 algorithm. The measurement outcome is compliant with the results of performed simulations. The TDOA standard deviation is presented in Table 3.

Table 3. TDOA standard deviation for different algorithms.

Algorithm	TDOA estimation standard deviation (σ)
M_1	2, 38 ns
M_2	2,24 ns
M_3	2,09 ns

Discussion and Conclusions

The results of performed measurements proved that the proposed method can improve the accuracy of TDOA estimation comparing to the standard algorithms (e.g. presented in the paper as M_1). Unfortunately the value of the error is still out of the target. Therefore author plans to investigate and improve proposed algorithm and perform additional research on the dependencies between TDOA estimations calculated with different methods. Finding such dependencies would possibly enable to reduce the error of the TDOA calculations in the indoor environments.

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