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Comparison of Detection Techniques for Multipath Propagation of Pseudolite Signals used in Dense Industrial Environments

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Abstract

Modern industrial environments with automated production machinery often require special indoor positioning and localization techniques, due to the presence of objects and of the infrastructure that may obstruct the line-of-sight propagation or interfere with the behaviour of electromagnetic waves. These challenges are difficult to overcome by the widely employed GNSS positioning system designed for use in outdoor areas. One of existing indoor positioning systems are the pseudolites, which transmit positioning signals similar to the ones used by GNSS systems. One of the sources of errors for pseudolites is the multipath propagation. Our paper compares the performances of several multipath propagation detection techniques, using Binary Offset Carrier (BOC) navigation signal and determines that errors increases sharply when the receiver uses navigation signals that have multipath propagation. The techniques that we present improve the positioning accuracy, which leads to more precise industrial processes.

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Keywords: indoor positioning; GNSS; pseudolite; multipath propagation; Binary Offset Carrier

1. Introduction

Modern industrial environments that employ automated production machinery, such as autonomous roving robots, self-guided vehicles or other types of nomadic equipment, often require special indoor positioning and

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localization techniques and systems in order to localize themselves in their surroundings [1]. Production, logistics, operation and maintenance processes and activities are constantly using information about position of each and every asset involved in the industrial environment and a high refresh rate of such information is a critical condition for meeting the requirements for increasing the flexibility of the production chain and shortening the production cycles. The same requirement for localization information applies for people moving in such complex indoor industrial environment.

The 'SmartFactory' concept and initiative developed and experimented by a group of important manufacturing companies [2] has also emphasized the importance of precise and efficient positioning and localization technologies in the industrial production environment, especially indoors. Furthermore, the Internet-enabled technologies, bringing the so-called 'Internet of Things' to industrial production domain, promote the execution of various production tasks by networked intelligent operating assets that integrate sensors and actuators and communicate with similar machines without operator's intervention. For autonomous nomadic devices, one important message to be included in this IP data traffic across industrial networks is the localization information of each operating asset it could interact with.

The above mentioned applications require positioning and navigation systems which can track the mobile robotic equipment also in indoor environments. The indoor positioning solutions that are already available on the market do not fully meet the multitude of requirements to operate with accuracy in harsh industrial conditions. A further obstacle for the designer of industrial equipment and processes is the lack of standardization of indoor positioning and localization systems in terms of the required hard- and software interfaces.

Already since 1990's, the predominant role in all applications requiring positioning and navigation was played by the systems based on satellite transmissions, the so-called Global Navigation Satellite Systems (GNSS), which provide users with precise information about their position in three coordinates on any point on Earth.

One of the main problems affecting the reception of signals from Global Navigation Satellite Systems (GNSS) in areas without ample clear sky visibility, including indoor environments, is represented by multipath propagation. This is mainly produced by reflection, diffraction and scattering caused by obstacles to the radio-frequency (RF) wave propagating to the receiver. Thus, apart from the signal travelling on the single-path (e.g. line of sight LOS) from the transmitter (e.g. the satellite), the receiver may also receive unwanted replicas of the signal, which travelled on longer paths. This creates positioning errors at the receiver. One way of mitigating this issue is by detecting which signals are received through single-path propagation. Afterwards, the receiver can use only these signals for determining its position with maximum accuracy. This can lead to more precise industrial processes, increased efficiency and cheaper manufacturing costs.

Pseudolites are used to improve the availability of navigation services in difficult environments, like indoor situations. They transmit positioning signals to dedicated receivers and may use advanced GNSS signals, such as BOC. The Binary Offset Carrier (BOC) modulation technique is used by the new generation of GNSS, such as modernized Global Positioning System (GPS), the European Galileo system and the Chinese COMPASS system. The paper compares the performances of several multipath propagation detection techniques, using BOC navigation signal. We use the detection techniques upon BOC signals travelling through difficult environments, with a variable number of propagation paths and poor Signal to Noise Ratio (SNR). These scenarios simulate pseudolite systems working in indoor industrial environments. The techniques that we present use the auto-correlation properties of the received BOC signals to detect the presence of multipath propagation and thus improve the positioning accuracy.

The next section of this paper gives a short overview of current GNSS indoor positioning systems. The third chapter describes the BOC navigation signal. The detection algorithms for multipath propagation are described in section 4. The fifth section explains the simulation environment and illustrates the simulation results. The last part of this work draws the conclusions and presents the possible directions of continuing the research.

2. Indoor positioning technologies relying on Global Navigation Satellite Systems

The complex physical layout and internal geography of indoor industrial environments often include a multitude of objects and moving pieces of infrastructure, but also electric and magnetic fields, that all concur to obstruct the normal line-of-sight visual observation or interfere with propagation and behavior of electromagnetic waves of different frequencies. Attenuation of electromagnetic waves due to propagation through building materials is one of the main sources of signal degradation affecting indoor positioning systems that rely on radio frequency signals. For example, at 1500 MHz frequency, building roofs or walls will introduce attenuation of: 1-4 dB for glass, 10 dB for tinted glass, 2-9 dB for wood, 5-31 dB for roof tiles or bricks and 29-33 dB for reinforced concrete [3].

The Global Navigation Satellite Systems (GNSS), such as the American Global Positioning System (GPS), the Galileo system of the European Union, the GLONASS system of Russia or Beidou-2/ Compass system of China, are today the standard technology for precision positioning, navigation and timing. These independent systems use different receivers, operational procedures and data processing techniques, but all require signal availability from a minimum of four GNSS satellites for three-dimensional positions fixes. Due to the above specified radio signal attenuation by building materials, all are almost useless in indoor industrial environments or underground production areas (e.g. pits, tunnels and mines). Several technologies have been designed and put in practice in order to address and mitigate this drawback.

1. One approach is the *Assisted GNSS*, where the satellite signal processing is supported by externally provided information. In this system, a GNSS receiver equipped with a mobile communications terminal (mobile phone) will connect to a dedicated location server with reference GNSS receivers and download ephemeris data and other information about satellites available in its area. This information will assist in finding and decoding weak signals from GNSS constellation and lead to faster position fixes and better accuracy in indoor environments [4].
2. *Pseudolites* are ground-based transmitters of GNSS-like signals ("pseudo-satellite"), which are installed inside buildings or underground and transmit signals in the GNSS frequency bands. Pseudolites are used to improve the availability of navigation services in difficult environments, such as indoors or in deep urban canyons, valleys, open pit mines. Dedicated receivers are used to perform pseudorange and carrier phase measurements on the pseudolite signals and determine position fixes. The main operational problems and sources of errors for pseudolites are: the near-far problem, multipath propagation, imprecise transmission positions and system synchronization [5].
3. A somehow similar system is the '*Locata*' developed by Australian based Locata Corporation (now part of Leica Corporation), which augments the GNSS signals with ground based transmitters and allow centimeter-level positioning accuracy, even when there are insufficient satellite signals for reliable positioning and navigation. The main component of the "Locata technology" is the time-synchronized pseudolite transceiver called a LocataLite. A network of LocataLites forms a LocataNet, which transmits GPS-like signals that allow single-point positioning using carrier-phase measurements for a mobile Locata receiver [6].

3. BOC modulation

Designers of the European GNSS have chosen the Binary Offset Carrier (BOC) method for the spread-spectrum modulation that is currently employed in Galileo Open Services, one of the reasons being the lower multipath susceptibility. The BOC method was also selected for the modernized GPS constellation and Compass signals. BOC modulation is a spread-spectrum modulation method that is currently employed in Galileo Open Services, GPS and Compass signals. The Sine BOC (denoted to as BOC) modulation separates the signal spectrum in two components, symmetrically located around the carrier frequency. This is obtained by multiplying the pseudorandom (PRN) code with a rectangular subcarrier [7]. The usual symbolization is BOC(f_{sc} , f_c) or BOC(m,n), with $m= f_{sc} / f_{ref}$ and $n= f_c / f_{ref}$, where f_c is the chip rate, f_{sc} is the sub-carrier frequency and f_{ref} is the reference frequency (generally f_{ref} =1.023 MHz). The resulting split-spectrum signal shows good frequency sharing and in the same time presents simple implementation, good spectral efficiency, high precision, and optimized multipath resolution [7]. The BOC modulated signal $x(t)$ is the convolution between a BOC waveform $S_{BOC}(t)$ and a modulating waveform $d(t)$, as follows [8]:

$$x(t)=\sum_{n=-\infty}^{+\infty} b_n \sum_{k=1}^{S_F} c_{k,n} S_{BOC}(t-nT_{sym}-kT_c)=S_{BOC}(t)\otimes \sum_{n=-\infty}^{+\infty}\sum_{k=1}^{S_F} b_n c_{k,n}\delta(t-nT_{sym}-kT_c) \,\square\, S_{BOC}(t)\otimes d(t) \tag{1}$$

where $\otimes$ is the convolution operator, $d(t)$ is the spread data sequence, b_n is the nth complex data symbol (in case of a pilot channel, it is equal to 1), T_{sym} is the symbol period, $c_{k,n}$ is the kth chip corresponding to the nth symbol, $T_c = 1/f_c$ is the chip period, SF is the spreading factor ($SF = T_{sym}/T_c$), and $\delta(t)$ is the Dirac impulse. It is considered that $d(t)$ is a wideband data signal, spread by multiplication with a PRN sequence. The Power Spectral Density (PSD) of MBOC is a combination of BOC(1,1) spectrum and BOC(6,1) spectrum. One method of producing the MBOC spectrum is that of utilizing Composite BOC (CBOC) time waveforms. The CBOC method is based on a weighted sum (or difference) of BOC(1,1) and BOC(6,1)-modulated code symbols [8]. Three implementations of CBOC have been developed: CBOC(+), CBOC(-) and CBOC(+/-). In this paper we will use the CBOC(-) modulation, defined as [9]:

$$s_{CBOC(-)}(t) = w_1 s_{BOC(1,1)}(t) - w_2 s_{BOC(6,1)}(t) \tag{2}$$

$$w_1 = \sqrt{10/11} \qquad w_2 = \sqrt{1/11}\ , \tag{3}$$

4. Algorithms for multipath propagation detection

While the multipath estimation problem has been widely addressed, e.g., in: [10-11], the topic of multipath detection is still of current interest, especially in dense urban environments. An innovative approach based on carrier phase has been investigated in [12-13]. The methods that we employ in this paper are derived from that approach. Our methods employ as an input the carrier phase information proposed in [12] and transform it into a scatter plot. The output is represented by the decision to declare or not that the received CBOC signal has travelled on a single path.

In order to detect the single/multi-path propagation, we defined three metrics of the scatter 'spread': one based on projections, a second one based on eigen-value decomposition and a third one based on the area covered by the scatter points. The first two methods shall be used here as a comparison for the performance of the area-based algorithm. These three algorithms have a relatively high practical value, as they can be easily implemented on software-defined radio receivers and can produce real-time detections.

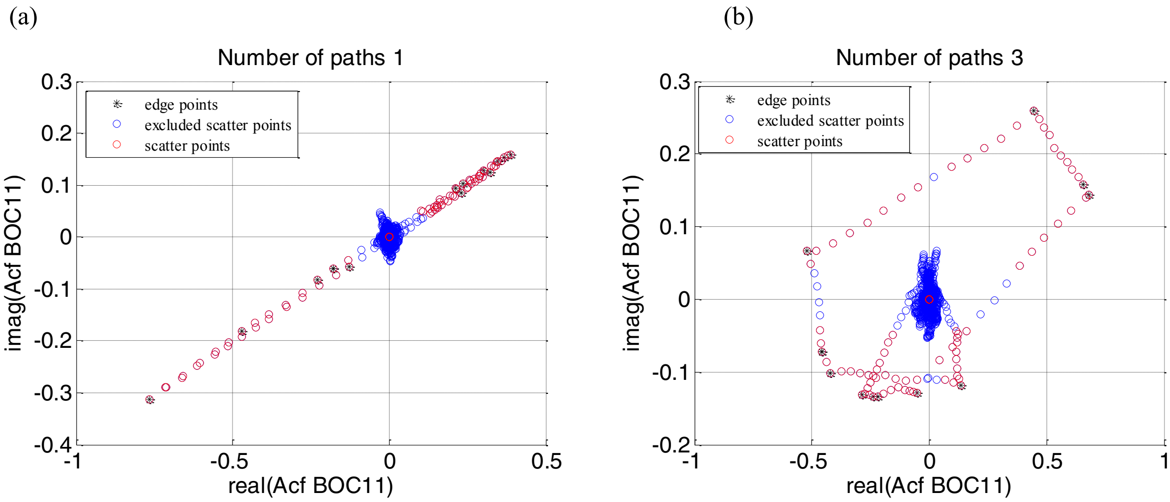

Fig. 1. (a) Example of ACF scatter points for single-path (b) Example of ACF scatter points for multipath.

These multipath detection algorithms employ the complex output of the autocorrelation function (ACF) between the received CBOC signal (e.g. from the satellite) and the locally generated CBOC signal. Figure 1 contains two examples of the scatter diagram of the real and imaginary parts of the ACF. All the dots in the diagram, no matter the color, constitute the scatter plot and present a certain pattern. As it can be seen, the majority of the scatter points obtained in the single path situation, illustrated in the plot on the left side, are approximately aligned across a straight axis. In contrast, in the multipath situation presented in Fig. 1(b), the points are arranged on the border of a polygon and inside it. The signal with multipath propagation can be detected by exploiting these patterns. Basically, one can say that as the spreading of the points decreases, the higher is the probability that the received GNSS signal had single-path propagation.

The first two algorithms enumerated earlier (projection and eigen-values), were detailed in [14]. The first method (denoted as the projection method) relies on the mean distance between each scatter point and the symmetry axis of the pattern, which is equal to the distance between the point and its projection on the axis. The second method (named as the eigen-value decomposition method) uses as measure (for the scattering of the points) the square root of the ratio of the eigen-values (also known as proper values) of the estimated covariance matrix between the real and imaginary parts of the ACF.

Seeking better performances, we developed and tested a novel technique (the third one used in this paper) based on the scatter area. The algorithm determines the surface of the area bordered by the points. As it can be seen in the plots in Fig.1, this area tends to be significantly lower for the single path case. To improve the probability for detection of the single-path signal, the algorithm increases the difference between the single-path area and the multipath one. For this, our algorithm identifies automatically the scatter points crowded around the origin of the axes and does not take them into consideration. The coordinates of these excluded points are lower in absolute value than a chosen threshold. These points are drawn in blue. Thus, the area is determined as the surface of the polygon formed by the edge points, drawn in black in Fig. 1.

Therefore, the area of the polygon may be used as an indicator of the multipath presence, and, if it exceeds a predefined threshold, then multipath propagation is declared. Otherwise, we consider the propagation as having a single path.

5. Simulation setup and results

To evaluate de performances of the previously described algorithms, we ran extended Monte Carlo simulations using Mathworks Matlab. The carrier-to-noise-density-ratio C/N_0 covers the [-20, 60] dB Hz interval. The lower C/N_0 values represent the situations when the GNSS signal suffers heavy attenuations (e.g. indoor), while the higher values characterize a line of sight propagation (e.g. rural environments). We assumed a dense urban scenario, modeled with a fading, uncorrelated, Nakagami propagation channel (m=0.8). The spacing between paths was taken in the [0, 0.35] interval. We did not employ navigation data, considering that pilot channels are available for the multipath detection purpose. The generated CBOC signal is passed through a radio channel modelled with Additive White Gaussian Noise. This navigation signal is also affected by multipath, in a controlled manner. The channel paths were randomly distributed between 1 and 10. In half of the simulations, the propagation was set to line of sight only. The rest of the simulations use between 2 and 10 channel paths. This corresponds to an environment with many large obstacles (e.g. urban canyons, mine pits, production halls).

The Detection probability P_d and the False Alarm probability P_{fa} constitute the final output of the Monte Carlo simulations. The detection probability is defined as the ratio between the number of correct detections of single paths and the total number of simulated single path propagations. False Alarm probability is expressed by the number of false multipath detections, divided by the total number of simulated single path propagations.

The resulting plots of P_d and P_{fa} are shown in Fig. 2 and 3. These figures show that the performances of the detection methods increase as the C/N_0 gets higher, because the noise is less powerful. For C/N_0 over 40 dB Hz, all methods obtain a P_d over 80%. At a C/N_0 under 0 dB Hz, the projection and eigen-values algoritms produce a P_d under 70%, while the P_d obtained by the area technique is higher than 70%. Thus it can be said that the novel method based on the scatter area works better.

Fig. 3 (b) illustrates the root-mean-square positioning error obtained for the two simulated scenarios: single-path and multipath. This is the error between the position computed by the GNSS receiver and its true location. It can be seen that it varies from over 200 meters at very low C/N_0 to approximately 0.30 meters at the highest C/N_0, in the single path propagation case. For this simulation, no multipath detection techniques were used. The purpose of the plot is to show that multipath propagation increases heavily the positioning error and that it is beneficial to use only signals that were received through a single path, in order to minimize the error.

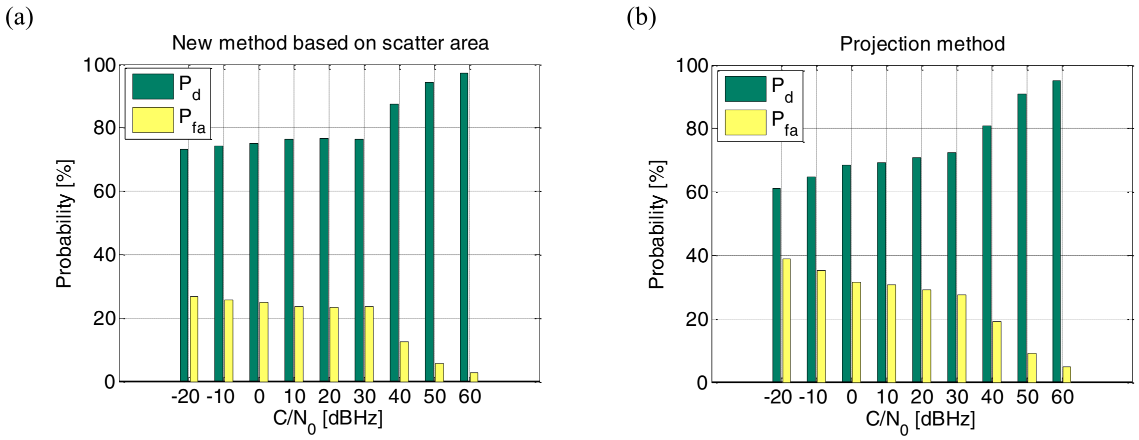

Fig. 2. (a) P_d and P_{fa} (for LOS only detection) vs. C/N_0, area method (b) P_d and P_{fa} (for LOS only detection) vs. C/N_0, projection method.

Conclusions

Modern industrial environments that employ automated production machinery often require special indoor positioning systems in order to localize equipment and resources. The localization information has to respect strict accuracy and availability standards to assure an efficient production flow. Traditional GNSS systems usually cannot provide the positioning services needed in difficult industrial environments, like mining areas or indoor sites.

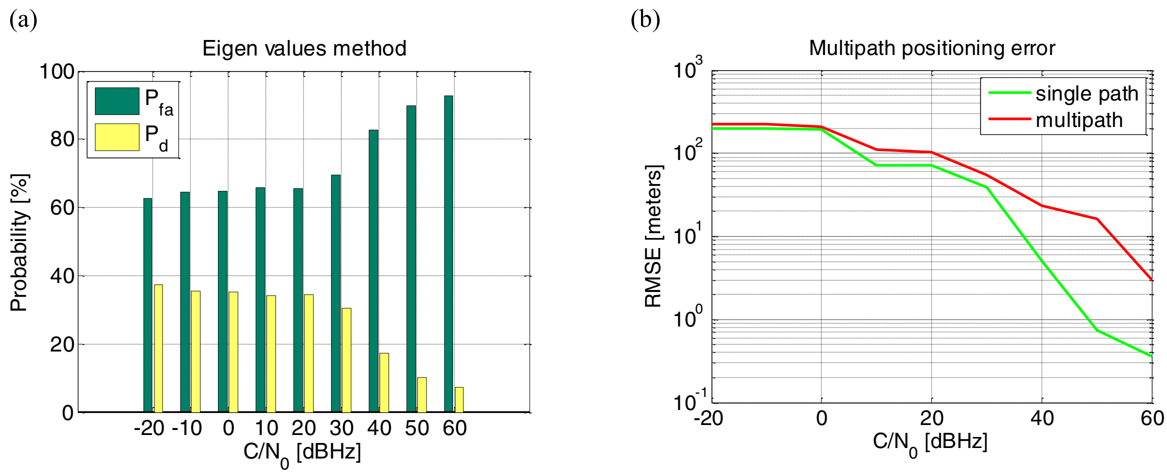

Fig. 3 (a) P_d and P_{fa} (for LOS only detection) vs. C/N_0, eigen-values method (b) Multipath and single-path positioning error vs. C/N_0.

One of the main issues that affects the accuracy of GNSS receivers in areas with numerous obstacles is the multipath propagation of the navigation signal. Fig. 3 (b) shows that, if the receiver uses only single-path signals, the positioning error decreases by as much as 20 meters in good C/N_0 situations.

The paper proposes a novel multipath propagation detection algorithm and compares its performances with two other detection techniques.

The area-based method shows an improvement of 4 - 10% of the P_d, with respect to the projection and eigen values methods. Even at low C/N_0 conditions, the P_d is over 70%. These results conclude that the proposed area method meets the requirements and has the capability to indicate to the receiver which GNSS signals should be demodulated for the best possible positioning accuracy in the majority of real life scenarios. Therefore, in an industrial facility, this improvement of the localization precision might raise the production efficiency and reduce the costs and amount of wasted resources.

For the future, we plan to implement these detection techniques on software-defined receivers and investigate their performances in indoor and urban experiments, which are of interest because of the multipath propagation and low-to-moderate C/N_0 conditions.

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