OFDM Signal Bandwidth Selection for Indoor Positioning System

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***Abstract*—In GPS denied environments like buildings there was unimaginable to wirelessly and electronically track members of rescue squads still few years ago. With today technologies the situation changed but there are still sever challenges to such system. Perhaps the most serious one is a direct signal separation from a bunch of its replicas caused by a multipath propagation. The aim of this article is to assess the problem of accurate direct signal time of arrival measurement in this situation. In the article the model of broadband transmitted and received signals modulated by OFDM are presented and methods of the direct signal delay estimation are described. Later the proper bandwidth for a sub meter accuracy of the range estimation is proposed based on modeling.**

Keywords—RTLS; UWB; OFDM; TDOA; Indoor positioning;

I. Introduction

The object position in outdoor environments could be nowadays easily determined using satellite navigation systems (eg. GPS) [1]. A different situation occurs at places with no or only a weak and sporadic GPS signal like in buildings. Here pseudolites may be used but they would be hardly installed in every building and industrial area. Still less such a system could be operable in the case of an accident or a fire. In these situations an autonomous positioning system deployed at the site upon the rescue team arrival is desired. A promising solution could be a hyperbolic TDOA system with transmitter tags attached to persons or robotic platforms entering the building and with several receiver stations situated outside the building.

One of the greatest challenges of this system is the direct signal separation from the clutter of its delayed replicas caused by signal scattering on surrounding obstacles. Only broadband signal and high resolution methods application allow this separation. Usually two types of broadband signals are used in such systems [2]: a narrow pulse (IR-UWB, [3]) or a multi-carrier signal (MC-UWB). After evaluation of both signal types a multi-carrier signal namely the OFDM [4], [5], was chosen for our system. Besides other things, the OFDM signal facilitates, as will be explained further, application of super-resolution methods.

The individual OFDM subcarriers are modulated by BPSK. A proper modulation code selection allows identification of individual transmitters and simultaneously this modulation spreads the signal power in time, eliminating power spike.

II. Signal Models

A. Transmitted and Received Signal Model

The transmitted signal $s_1(t)$ is formed by subcarriers waves with frequencies $f_n = (n_0 + n - 1)$, $n = 1, 2, \ldots N$. Each subcarrier is BPSK modulated, that is multiplied by a coefficient $A_n = \pm 1$. The bandwidth of the signal is equal to $BW = N.f_0$. The transmitted signal envelope represents the pulse with duration of $T_s > T_0 = 1/f_0$ (the interval of orthogonality), starting at the time t_0 (it is actually a single OFDM symbol interval):

$$s_1(t) = \sum_{n=1}^{N} A_n \exp\left[j 2\pi f_0 (n_0 + n - 1) t\right] \quad \text{for } t \in \langle t_0, t_0 + T_S \rangle. \tag{1}$$

Due to multipath propagation the transmitted signal arrives at the receiver as a linear combination of the direct signal, its delayed replicas and a Gaussian noise η. The model of the received signal $s_2(t)$ can then be written as ([6]):

$$s_2(t) = \sum_{l=0}^{L} a_l s_1(t - \tau_l) + \eta(t). \tag{2}$$

The received signal contains information on the direct signal delay and complex amplitude. As the direct signal we consider the contribution $a_0 s_1(t - \tau_0)$. The replicas delays form the $\{\tau_l\}_{l=1 \text{ to } L}$ sequence. After the reception the signal is converted into baseband and sampled:

$$s_{2s}(t_k) = s_2(t_k) \exp(- j 2\pi n_0 f_0 t_k). \tag{3}$$

The signal $s_{2s}(t_k)$ consists of the received signal complex envelope samples. The samples number within the interval of orthogonality T_0 is $M = f_s.T_0$. To reach a greater time of arrival estimation accuracy the sampling frequency f_s is chosen substantially greater than the threshold value of *2.BW*.

III. Direct Signal Delay Estimation

The time delay of the direct signal estimation can be done in several ways. For this purpose there are typically used either a cross-correlation method or function (CCF), or some of high resolution spectral adaptive methods [7] (SAM).

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A. Use of Cross Correlation Function

Hereafter, this method will use abbreviation of CCF method. The sampled signal $s_{2s}(t_k)$ is correlated with the sampled transmitted signal model $s_{1s}(t_k)$ resulting in a cross-correlation function with a maximum at a point corresponding to the delay of the direct signal $\tau = \tau_0 + t_0$ containing also unknown transmission time instant t_0. The unknown moment t_0 included in all the measured times of arrival at all receivers is eliminated by the TDOA method. The aim of this delay measurement method is to find the beginning of the received pulse. This information, however, is also required in spectral methods application.

B. Use of Adaptive Spectral Methods

After finding the beginning of any pulse by the correlation function a signal portion of length [6] T_0 is selected and sampled by $N > 2M$ samples:

$$s_{2s}(t_k) = \sum_{n=1}^{N} b_n A_n \exp[j2\pi f_0 (n-1) t_k] + \eta(t_k) \exp(-j2\pi n_0 f_0 t_k),$$

where $k = 1$ to M and

$$b_n = \sum_{l=0}^{L} a_l \exp[-j2\pi f_0 (n-1)\tau_l], \tag{4}$$

is the complex amplitude of the n-th subcarrier. We see that the complex amplitude $\{b_n\}$ of the received signal subcarriers are containing information on delays $\{\tau_l\}$ of the direct signal *(l = 0)* and of all other replicas *l = 1 to L*. To obtain the coefficients b_n the DFT of the acquired M signal samples is performed and the first N complex amplitudes are then multiplied by the coefficients A_n which ensures demodulation. This results in a sequence of coefficients $\{d_n\} = \{b_n\} + \{\eta_n\}$, which consist of complex amplitudes subcarriers b_n and noise components η_n. This process can be described as:

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{DFT}\left[s_{2s}(t_k)\right]_{n=1}^{N}, \tag{5}$$

where: $\mathbf{DFT}\left[s_{2s}(t_k)\right]_{n=1}^{N}$ is the column vector of the first N coefficients of the DFT, $\mathbf{A}$ is the NxN diagonal matrix whose diagonal elements are equal to the modulation coefficients $\{A_n\}$ and $\mathbf{d}$ is a column vector of n elements: $d_n = b_n + \eta_n$.

The resulting vector $\mathbf{d}$ is thus formed by a linear combination of complex exponentials $\exp[-j2\pi f_0(n-1)\tau_l]$ and white noise $\{\eta_n\}$. The vector $\mathbf{d}$ (the sequence $\{d_n\}$) spectrum will therefore probably peaks at the frequencies of these complex exponentials $\theta_l = 2\pi f_0 \tau_l$. Then it is possible to obtain the delays τ_l by a spectral analysis of the sequence $\{d_n\}$ using either repeatedly the DFT or some of the high resolution adaptive spectral analysis methods on this sequence.

IV. Adaptive Spectral Methods

Adaptive spectral analysis methods estimate the frequencies and complex amplitudes of the complex exponentials in uncorrelated Gaussian noise [8]. They can be divided into several types i.e. nonparametric, parametric and subspace methods [9]. The non-parametric methods include, for example, the periodogram or the Capon methods. The parametric methods comprise Burg method, covariance and modified covariance method and the MUSIC methods, eigenvectors (MinNorm) or the ESPRIT methods are called the subspace methods. Accuracy and resolution of these methods are discussed in [6] and [9]. From simulations, presented in the previous article [9] the modified covariance method [10] was chosen as the most appropriate in our case.

V. Bandwidth Selection

In time measurement systems, the signal bandwidth *(BW)* plays a leading role in distance resolution. It directly affects the achievable pseudorange measurement error, caused by noise, but also the error due to multipath propagation (the presence of other delayed replicas of the transmitted signal). In case of using the cross-correlation function (CCF) the range resolution ΔD can be determined from the formula:

$$\Delta D = c/BW, \tag{6}$$

where c is the speed of light.

In this section, we will describe the analysis of the dependency of resolution capabilities of the both methods on bandwidth. Important parameters in terms of the pseudorange measurement errors are bandwidth *BW*, amplitude, phase and time delays of other replicas of the received signal and the signal-to-noise ratio (*SNR*). The following simulations show the dependence of the pseudorange measurement error in both methods on the bandwidth and *SNR*. For this simulation model two receivers P1 and P2 were chosen with antennas at the same distance from the transmitter antenna. At the first receiver P1 only a direct signal is received, serving as the reference signal. At the P2 receiver the direct signal and a replica with the same amplitude are received. Such a simplified model is useful for demonstrating the properties of the system. The generated signal bandwidth was adjusted in the range of 25 MHz to 325 MHz and the SNR varied from -20 to +25 dB.

VI. Simulation Results

In figures 1, 2 and 3 results of mean pseudorange difference errors, abbreviated here as DOD (Difference of Distances) computation by the SAM method are shown. We can see the DOD dependence on the bandwidth *BW* and ratio *SNR* for three selected distances of the replica from the direct signal (0.65, 1.6 and 3.5 m). It is obvious that the error decreases with the bandwidth and with signal-to noise ratio.

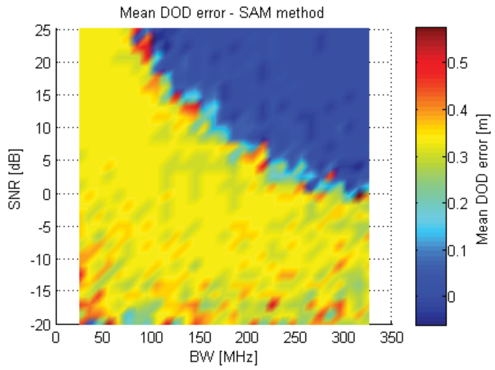

Fig. 1. Mean DOD error computed by the SAM method for replica distance from the direct signal of 0,65 meters.

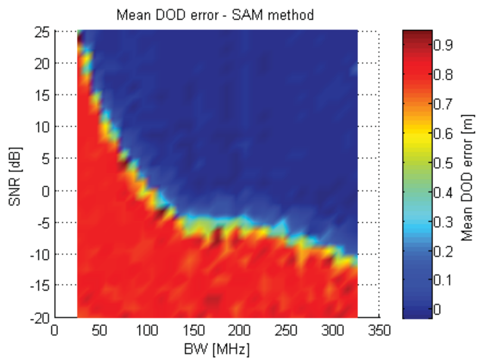

Fig. 2. Mean DOD error computed by the SAM method for replica distance from the direct signal of 1,6 meters.

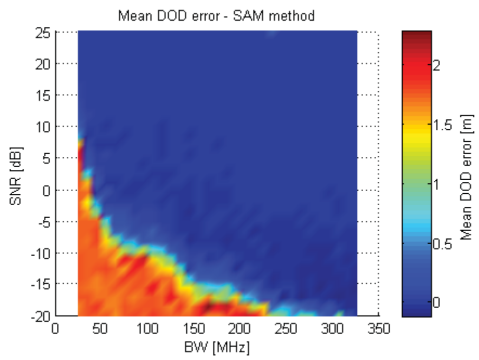

Fig. 3. Mean DOD error computed by the SAM method for replica distance from the direct signal of 3,5 meters.

In the figures 4, 5 and 6 there are shown again the mean errors dependences of DOD on *BW* and *SNR*, but this time the calculations were carried out using the CCF method. In this case the errors depend mainly on the signal bandwidth and only negligibly on the *SNR* ratio which could be explained by a lower resolution capability of this method.

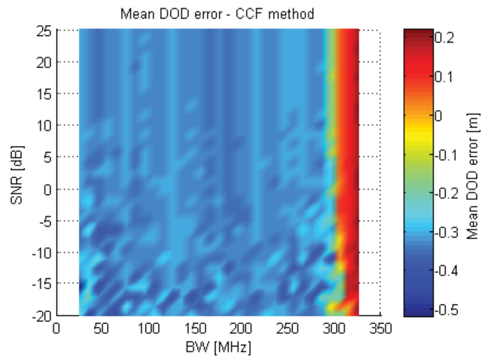

Fig. 4. Mean DOD error computed by the CCF method for replica distance from the direct signal of 0,65 meters.

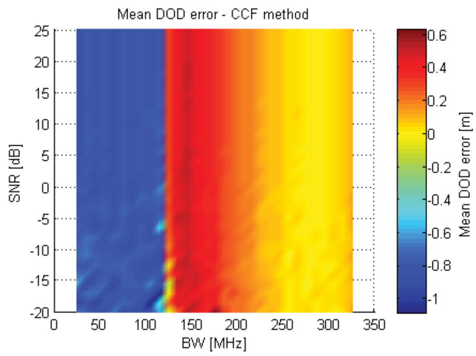

Fig. 5. Mean DOD error computed by the CCF method for replica distance from the direct signal of 1,6 meters.

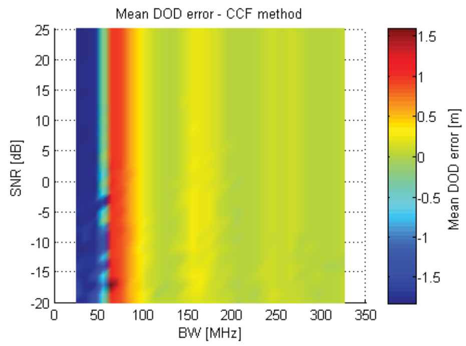

Fig. 6. Mean DOD error computed by the CCF method for replica distance from the direct signal of 3,5 meters.

When analyzing the both methods in more details we can conclude that there are several phases of the range errors dependence on the replica distance ρ. In the figure Fig. 7 and Fig. 8 the DOD calculations using both methods are compared. The blue curves represent the reference signal responses with their maxima at the zero and the red curves correspond to the received signals with replicas.

In the first phase the methods do not resolve the replica from the direct signal because of a small signal bandwidth or because the replica is too close. This first step is illustrated in Fig. 7 - A), and Fig. 8 - A). The error is positive and gradually increases with the replica distance.

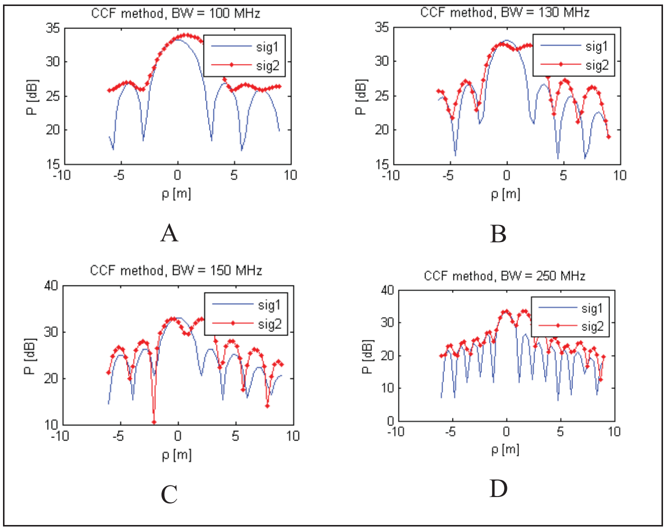

Fig. 7. DOD estimation by the CCF method the replica distance from the direct signal of 1,6 meters.

The second phase occurs at the replica distance near the method resolution ability. This is seen in the Fig. 7 - B) and Fig. 8 - B). In the method CCF the error that was originally positive changed to a nagative value. In the SAM method the situation is similar, but in the case of a narrowband signal, even a greater error is possible in this phase (e.g. in the Fig. 8 B) an error of 1.2 meters is demonstrated).

The third phase comes when the methods already resolve the replica of the direct signal and two peaks are seen in the Fig. 7 - C), D) and Fig. 8 - C), D). Here we can see that with the CCF method the error gradually decreases reaching the correct value, at about BW = 250MHz and with the SAM method the error has almost zero value around BW = 130MHz.

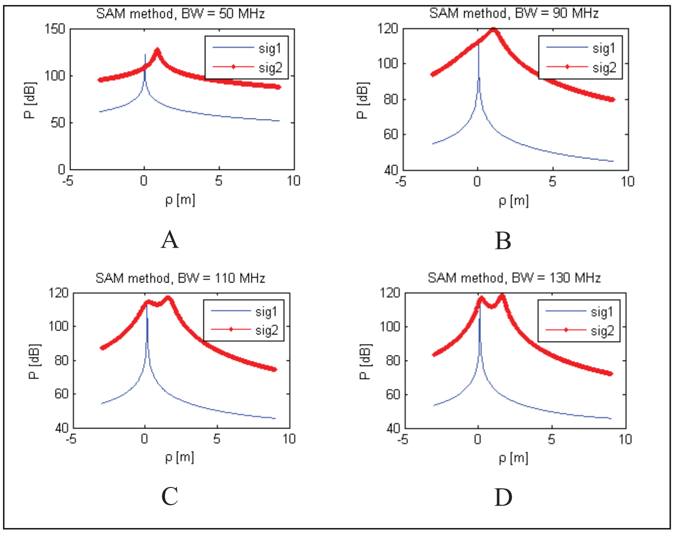

Fig. 8. DOD estimation by the SAM method for the replica distance from the direct signal of 1,6 meters.

VII. Conclusion

The article outlined a system for people positions determination in buildings based on TDOA. Two methods of the time of arrival measurement were analyzed in terms of their ability to separate the direct signal from its replica due to the multipath propagation in noise. The executed simulations show a high importance of using sufficiently large signal bandwidth for this goal. For example a 200 MHz bandwidth at SNR around 10 dB makes possible to measure the DOD with an error of less than 1 m even with close replica.

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