A novel high precision SDR-based positioning system

G. Piccinni, G. Avitabile, G. Coviello
Electrical and Information Engineering Department
Polytechnic University of Bari
Italy
{g.piccinni, gfa, g.coviello}@poliba.it

C. Talarico
Electrical and Computer Engineering Department
Gonzaga University, Spokane, WA
USA
talarico@gonzaga.edu

Abstract— **This paper introduces a novel positioning system based on a Software Defined Radio (SDR) architecture that evaluates with a high level of accuracy and precision the position of an active target placed in a harsh environment. The use of an SDR architecture allows the properties of the transmitted signal to be varied according to the accuracy and precision required by diverse applications and operating conditions. The positions are extracted using a fully-digital algorithm implemented with an FPGA. Transmitting a 64-length OFDM symbol of only 100 MHz of bandwidth, the proposed system achieves an accuracy that is within one cm.**

Keywords; Indoor Positioning System, Localization, OFDM, Software Define Radio; Zadoff-Chu sequence

I. INTRODUCTION

The aim of this work is to introduce a software reconfigurable indoor positioning system able to evaluate the position of an active device with a high-level of precision and an accuracy that is suitable for medical monitoring. The proposed system relies on the use of a cluster of SDR receivers and a non-coherent demodulation scheme. The SDR architecture guarantees system re-configurability as a function of design specifications, and it requires a very basic analog front-end, composed of a down/up-conversion mixer, a low-noise power-amplifier, an A/D converter, and a D/A converter. The system operates well in presence of severe multipath conditions and relies on a full digital signal whose characteristics, including bandwidth, period and gain, can be modified via software.

II. SYSTEM ARCHITECTURE

The proposed system measures the 2-D and 3-D positions of an active target exploiting a GPS-like scheme composed by four receivers. One of them is selected as reference of the system and so the positions are computed evaluating the Time-Difference-of-Arrival (TDOA) of the received signal. The transmitter sends an OFDM-like signal to the four receivers. The receivers (RX) compute their relative distance from the transmitter (TX) and then send the information to a central server that has the function of triangulating the TX position. The OFDM symbol comprises only pilot subcarriers which represent a coefficient of a Zadoff-Chu sequences (ZC) [1]. The use of these sequence allows to exploit a Software Define Radio (SDR)-based architecture for both the transmitter and the receivers (Fig. 1). Once generated the coefficients of a ZC sequence can be stored in a lookup table and converted in an I/Q analog baseband signal by means of a

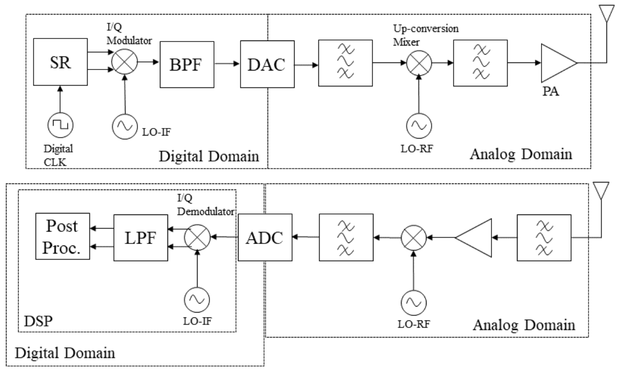


Figure 1. System Architecture (a) Transmitter (b) Receiver.

Digital to Analog converter. At the receiver side, the analog front-end translates the RF signal into an IF signal and then feed it to an Analog to Digital converter that transforms the analog signal into digital samples. The distances and the target positions are computed by means of a fully digital algorithm implemented with an FPGA. The resulting system architecture is easily and widely scalable as function of the operating spatial resolution and the precision required. The signal period (T), the bandwidth (B), and the number of subcarriers can be varied through a very modest software modification. Moreover, the proposed system requires the same analog front-end for both the transmitter and the receivers, and, as long as it can be designed to cover a wide range of bandwidths, allows to leave to the digital section of the system the tasks of filtering, demodulating and modulating. Finally, since the I/Q demodulation and modulation is performed in the digital domain, any offset or mismatch in amplitude, frequency, and phase between the I/Q paths can be easily avoided or recovered via the software algorithm.

III. SYSTEM ANALYSIS

As mentioned, the distances and the positions of the transmitter and the receivers are extracted with a TDOA algorithm. Hence, no synchronization mechanism is implemented between the transmitter and the receivers. However, the receivers share the same clock to generate the time acquisition signal and the same local oscillator (LO) source needed by the down-conversion process. This way, any temporal shift or carrier frequency offset between the transmitter and the receivers appear as constant terms in the distance computation and therefore they can be removed using multiple TDOA measurements. The distance ranging algorithm was presented in

[2] and requires four steps. In the first step the starting point of the sequence, is correctly computed and selected, for the reference receiver. In the second step a coarse difference of distances is evaluated in the time domain by performing the cross-correlation function between the receivers' signals and a clean copy of the transmitted signal. In the third step the previous values are finely adjusted computing the carrier offset between the subcarriers in the frequency domain and finally in the last step the position is extracted considering a geometrical model of the system. However, the presence of multipaths can affect the distance values extracted with the proposed algorithm [2]. Thus, the third step is slightly modified to include the generation of a Finite Impulse Response (FIR) filter that allows to remove the multipath echoes [3]. The coefficients of the FIR filter are extracted considering the properties of the cross-correlation function of the ZC sequences. The cross-correlation function presents a series of peaks that represents the direct signal and its copies generated by the obstacles of the indoor environment (Fig. 2). The presence of multipaths, in time domain, modifies the amplitude and the position of the main peak and the FIR coefficients can be computed and adjusted by means of well-known gradient methods. The criterion used relies on the error in time-shift and amplitude estimation:

$$\begin{aligned} \boldsymbol{F}_1 &= \hat{\boldsymbol{\tau}}_i - \boldsymbol{\tau}_{i-1} \\ \boldsymbol{F}_2 &= \hat{\boldsymbol{\alpha}}_i - \boldsymbol{\alpha}_{i-1} \end{aligned} \tag{1}$$

where $\hat{\boldsymbol{\tau}}_i$ and $\hat{\boldsymbol{\alpha}}_i$ are the time-shift and the amplitude of the FIR coefficients estimated at i^{th} iteration cycle step. Using the method of steepest descent to minimize the cost function (1) the coefficients are updated according to:

$$\begin{aligned} \boldsymbol{\tau}_i &= \hat{\boldsymbol{\tau}}_i - \gamma_1 \cdot \boldsymbol{F}_1 \\ \boldsymbol{\alpha}_i &= \hat{\boldsymbol{\alpha}}_i - \gamma_2 \cdot \boldsymbol{F}_2 \end{aligned} \tag{2}$$

The coefficients γ_1 and γ_2 determine the convergence speed of the algorithm and are dynamically adjusted in each iteration cycle. The value of γ_1 varies in range from 0.1 to 1.5 while γ_2 is chosen in the range from 0.1 to 1.1. The increment of these coefficients is inversely proportional to the standard deviation of the functions F1 and F2 and determine the stop condition of the algorithm. The algorithm is terminated, i.e. it has minimized the expression (1) and estimated the multipath peaks when there are no longer variations in the amplitude and the time-shift of the multipath peaks. Once the termination condition is achieved, the coefficients of the FIR filter are set, and therefore the equalized signal $x_{eq}(z)$ can be computed (by convoluting the FIR filter with a clean copy of the transmitted signal), and the received signal $y_r(z)$ extracted.

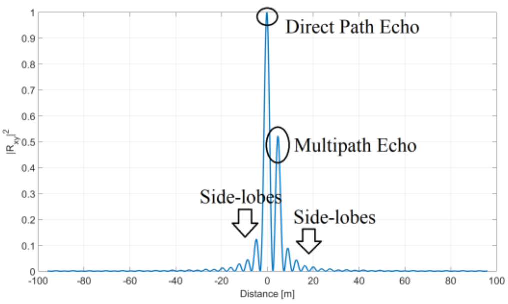
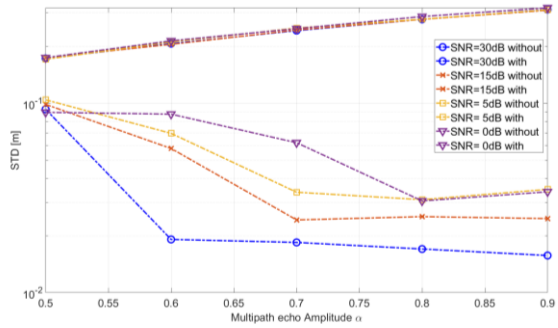
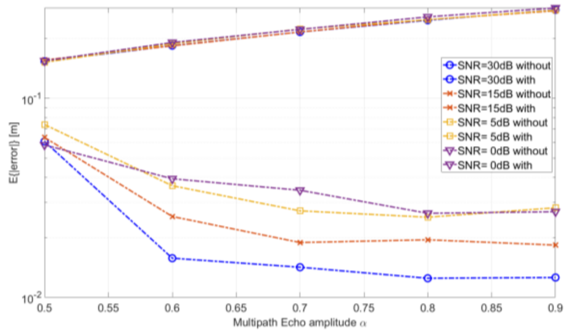


Figure 2. Cross-Correlation in time domain in presence of multipath echo



(a)



(b)

Figure 3. (a) System precision and (b) System accuracy as function of multipath amplitude and SNR.

The system was validated considering a channel impulse response comprises of a fixed direct path and a single multipath echo with a variable amplitude. The distance of the multipath echo is varied, and the performances are extracted as function of the SNR of the system exploiting a 64-length OFDM symbol with 100 MHz bandwidth. Fig. 3 shows how the use of the echo cancellation algorithm improves the overall distance accuracy. In facts, the system is able to compute the TDOA with an accuracy that is within one cm even in presence of severe multipath conditions and for low SNR.

CONCLUSIONS

A novel solution is presented to implement an indoor positioning system that exploits an SDR-based architecture for both the transmitter and the receiver. The resulting system is easily and widely scalable as function of the operating spatial resolution and the precision requirements. Exploiting the properties of the transmitted signal a simple algorithm is implemented to estimate and remove the multipath echo. With the use of a 100 MHz 64-length OFDM symbol and a fully-digital distance ranging algorithm, the proposed system achieves a precision providing an accuracy that is within one cm even with low SNR and in presence of severe multipath conditions.

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