Performance Analysis of TOA Range Accuracy Adaptation for Cognitive Radio Systems

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***Abstract*—Location awareness is a prominent feature of cognitive radio (CR) systems. In order to support goal driven and autonomous location aware applications using CR systems, range accuracy adaptation is an essential task. Therefore, in this paper, performance analysis of optimal maximum likelihood (ML) time of arrival (TOA) range accuracy adaptation technique is conducted to study performance limits of location aware systems. The performance of ML-TOA range accuracy adaptation method is evaluated in dynamic spectrum access environments through computer simulations. The results show that range accuracy adaptation can be achieved by ML-TOA method with a relative error for each desired range accuracy.**

I. Introduction

Cognitive radio (CR) is a promising technology to develop advanced and intelligent wireless systems [1]. Goal driven and autonomous location awareness is an integral part of CR systems [2]-[4]. Since range accuracy is one of the most fundamental performance metrics of location aware systems, range accuracy adaptation plays a vital role for supporting goal driven and autonomous location aware applications [2].

Range adaptation is one of the main cognitive behaviors of bat echolocation system [2], [5]. The bats using frequency modulation (FM-bats) for the emission make adjustments on the emitted-sound duration, bandwidth, and repetition rate during the target (e.g. insect) approach. For instance, as the FM-bat gets closer to its target, it decreases the transmitted signal duration and increases the burst repetition rate. This is accomplished by using the feedback information (i.e. the distance to the target) provided by the receiver mechanism in the bats. As a result, by inspiring from the range adaptation skill of the bats, the idea of time of arrival (TOA) range accuracy adaptation method for Cognitive Positioning Systems (CPS) is first introduced in [3]. The proposed TOA range accuracy adaptation method utilizes Cramer-Rao Lower Bound (CRLB) information at the transmitter as the parameter optimization criterion since it shows the relationship between range accuracy, transceiver and channel environment parameters. In [2], it has been stated that maximum likelihood (ML) can be used at the receiver side of range accuracy adaptation in order to achieve the desired range accuracy dictated by CRLB.

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Notice that performance analysis of ML-TOA range accuracy adaptation method has not been studied in the literature. Therefore, performance analysis of optimal ML-TOA range accuracy adaptation method is conducted in this paper.

The remainder of the paper is organized as follows; Section II provides the system model. In Section III, the expression for optimization criterion and ML-TOA range accuracy adaptation technique are presented. In Section IV, simulation results are provided and discussed. Finally, the conclusions are given in Section V.

II. System Model

The system model shown in Fig. 1 is considered in this paper. In this model, an optimization criterion is used to determine transmit parameters in order to adapt the range accuracy to the desired range accuracy value. In what follows, adaptive waveform generation feature of CR systems is used to generate the waveform based on parameters obtained from the optimization algorithm. The generated signal is transmitted over channel and processed by adaptive waveform processing feature of CR systems to obtain the corresponding baseband signal. Finally, time of arrival path is estimated using time delay estimation method.

Lets consider the baseband transmit signal $s(t)$ with absolute bandwidth of B ($[-B/2$,$B/2]$), which is given by

$$s(t) = \sum_{l} d_l p(t - lT_s) \ , \tag{1}$$

where d_l is the real data for lth symbol, $p(t)$ is the pulse signal with energy E_p and duration T_p, i.e., $p(t) = 0$ for $t \notin [0, T_p]$ and T_s is the symbol duration. The baseband signal $s(t)$ is transmitted over AWGN channel and the corresponding baseband representation of receive signal $r(t)$ is given by

$$r(t) = \alpha s(t - \tau) + n(t) \ , \tag{2}$$

where α and τ are the path coefficient and delay, respectively, and $n(t)$ is independent white Gaussian noise with spectral density of σ^2. At the receiver side, $r(t)$ is used to perform ML time delay estimation. Note that the main objective of ML-TOA range accuracy adaptation is to achieve given desired range accuracy as accurate as possible considering available

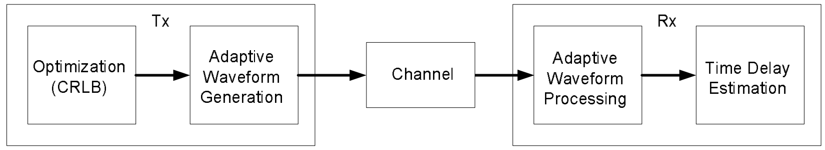

Fig. 1. System model for range accuracy adaptation.

resources. In the following section, CRLB optimization criterion along with ML time delay estimator for range accuracy adaptation is provided.

III. Range Accuracy Adaptation

Let τ represent the unknown signal parameter, where α is assumed to be known. The observation interval $[0, T]$ is considered and it can be expressed as $T = NT_s$, where N is the number of observation symbol. Then, the ML estimate for τ is given by [6]

$$\hat{\tau}_{\mathrm{ML}} \approx \arg\max_{\tau} \left\{ \frac{1}{\sigma^2} \int_0^T \alpha r(t) s(t-\tau) \mathrm{d}t \right\} \ , \tag{3}$$

Using (3), approximate CRLB expression is given by [6],

$$\mathrm{CRLB} = \frac{1}{\frac{4\pi^2}{3}\mathrm{SNR}B^2} \ , \tag{4}$$

where SNR is defined as

$$\mathrm{SNR} = \frac{\alpha^2 N d_l^2 E_p}{\sigma^2} \ . \tag{5}$$

Note that the ML-TOA range accuracy adaptation utilizes (4) as the optimization criterion. We assume that spectrum awareness engine has already the available spectrum information, i.e. B and environment awareness engine has the complete knowledge of the channel environment, i.e. α [2]. In addition, it is assumed that CRs setup ranging parameters (e.g. SNR, B) through cognitive ranging protocol [2]. Finally, we assume that channel changes faster than the available spectrum. As a result, the steps for the proposed ML-TOA range accuracy adaptation are given as follows:

1) Location awareness engine obtains the desired range accuracy σ_d from the cognitive engine.
2) Location awareness engine requests and receives the available spectrum information and channel parameters from spectrum and environment awareness engines, respectively.
3) Location awareness engine performs the optimization to determine the transmission parameters, i.e. B (SNR is assumed to be fixed and known) for given $\tilde{B}$, where $\tilde{B}$ is the vector representing the available absolute bandwidth.
4) Determine all the candidate range accuracy $\tilde{\sigma_d}$ for all the available bandwidths in $\tilde{B}$ using the following equation (i.e. $\sqrt{\mathrm{CRLB}}$)

$$\tilde{\sigma_d} = \frac{c}{\sqrt{\frac{4\pi^2}{3}\mathrm{SNR}\tilde{B}^2}} \ . \tag{6}$$

where c is the speed of the light.
5) Select the optimal B using minimum square error (MSE) metric, i.e. $min(\tilde{\sigma_d} - \sigma_d)^2$.
6) CR transmitter sends the transmission parameters to the receiver in order receiver adapt itself to the parameters.
7) Adaptive waveform generator generates the waveform based on the transmit parameters.
8) CR transmitter transmits the signal and the CR receiver process the signal using adaptive waveform processor and then estimates time delay using ML-TOA estimator.

Note that the flowchart for the optimization algorithm is shown in Fig. 2.

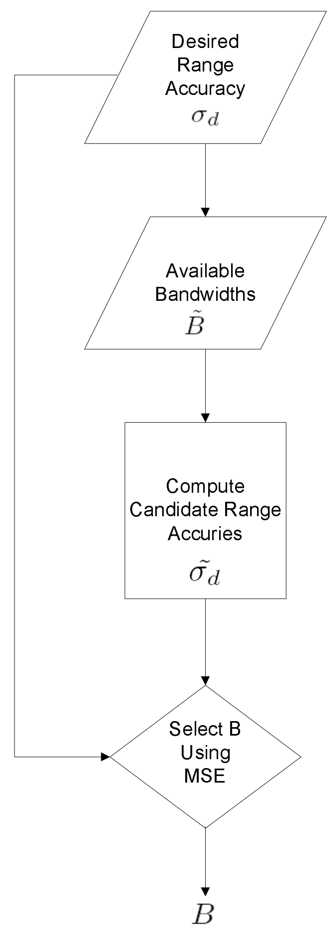

Fig. 2. Flowchart for the optimization in range accuracy adaptation.

IV. Simulation Results

The performance of ML-TOA range accuracy adaptation algorithm is investigated through computer simulations.

Assuming that we have a sequence of range accuracy requested by cognitive engine over a period of time. The desired range accuracy can be random due to goal driven and autonomous operation of cognitive radios. Therefore, we assume that range accuracy has a uniform distribution within $\sigma_{d,min}$ and $\sigma_{d,max}$ limits, i.e. $\mathcal{U}[\sigma_{d,min}, \sigma_{d,max}]$, where $\sigma_{d,min}$ and $\sigma_{d,max}$ are the minimum and maximum desired range accuracy, respectively. As a result, here, it is assumed that $\sigma_{d,min} = 8$m, and $\sigma_{d,max} = 17$m, i.e. $\mathcal{U}[8, 17]$.

Unlike to the conventional wireless systems, the utilized spectrum in CR systems can be dynamic in addition to propagation channel. This implies that the transmission parameters (e.g. bandwidth, carrier frequency) can be dynamic in CR systems. Such dynamic behaviors can introduce additional dynamism into propagation channel. Consequently, the receiver needs to be adaptive to cope with the changes in transmitter and propagation channel. Therefore, for the performance evaluation of CR systems, there is a need to develop statistical modeling of dynamic spectrum utilization as well as CR propagation channel. To the best of authors' knowledge, there is not any solid study in the literature on statistical modeling of spectrum utilization and CR propagation channel. Therefore, in order to evaluate the performance of ML-TOA range accuracy adaptation, a simple statistical dynamic spectrum utilization model and a single path AWGN channel is assumed in this study.

Theoretically, dynamic spectrum utilization can be modeled with four random variables, which are number of available band (R), carrier frequency (f_c), corresponding bandwidth (B), and power spectral density (PSD) or transmit power (P_{tx}). Without loss of generality, we assume that PSD is constant and it is the same for all available bands. Furthermore, we assume that all the bands have the same noise spectral density, which results in a fixed SNR value for all the bands. Since we consider baseband signal during analysis, the effect of f_c such as path loss are not incorporated into the simulations. In addition, R is assumed to be deterministic. Therefore, B is the only random variable considered during the generation of dynamic spectrum utilization in the simulation environment. As a result, B is assumed to be a uniform random variable within B_{min} and B_{max} limits, i.e. $\mathcal{U}[B_{min} B_{max}]$, where B_{min} and B_{max} are the minimum and maximum available absolute bandwidths, respectively. $B_{min} = 0.5$MHz and $B_{max} = 1$MHz are employed for the simulations. The rest of the dynamic spectrum utilization parameters are given as follows: $R = 100$, $SNR = 17$dB, and $N = 1$. The results are obtained over 3000 different channel realizations. Furthermore, we assume that $|\alpha| = 1$ provided by the environment awareness engine to the location awareness engine. The following pulse shape is employed

$$p(t) = A\left(1 - \frac{4\pi t^2}{\zeta^2}\right) e^{-2\pi t^2/\zeta^2} \ , \qquad (7)$$

where A and ζ are parameters that are used to adjust the pulse energy and the pulse width, respectively. A is selected in order to generate pulses with unit energy. For the given pulse shape, pulse width is defined as $T_p = 2.5\zeta$ [7]. During the transmission, the energy of transmitted signal is normalized to 1. Finally, ML-TOA estimator is utilized to estimate time delay in the receiver side.

In Fig. 3, the performance of ML-TOA range accuracy adaptation is plotted and compared against the desired and approximate CRLB. In theory, if there is infinite number and value of available bandwidth and SNR, the approximate CRLB follows the desired range accuracy exactly. However, in practice, since the number and value of available bandwidth is finite, there can be a slight margin between the approximate CRLB and desired range accuracy shown in Fig. 3. On the other hand, the ML follows the approximate CRLB with a margin for each desired range accuracy value. According to the results in Fig. 3, the first desired accuracy is 11m and the estimated range accuracy based on approximate CRLB is 10.96m. On the other hand, the estimated range accuracy in receiver side using ML method is 10.06m. As a result, the margin between the approximate CRLB and ML is 0.90m. This margin is due to the performance difference between the approximate CRLB and ML-TOA estimator [6]. The corresponding error margin between desired and ML as well as between desired and approximate CRLB for the results in Fig. 3 is shown in Fig. 4 in terms of relative error metric e, which is defined as

$$e = \frac{\sigma_d - \sigma_{\hat{d}}}{\sigma_d} \ . \qquad (8)$$

According to Fig. 4, relative error performance of ML-TOA range accuracy adaptation algorithm is different for each desired range accuracy value with the fluctuations around 0.1.

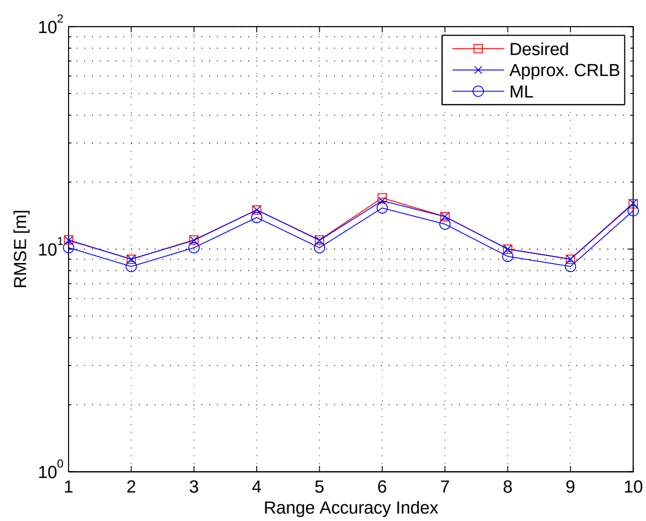

Fig. 3. Performance of ML-TOA range accuracy adaptation.

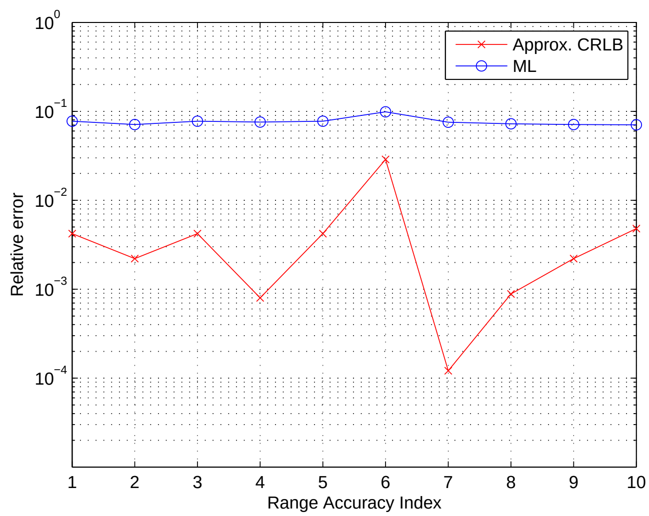

Fig. 4. Relative error of ML-TOA range accuracy adaptation and approximate CRLB.

Range accuracy adaptation is performed by adapting only bandwidth parameter in this paper. Therefore, the corresponding bandwidth adaptation for the results in Fig. 3 is plotted in Fig. 5. For instance, the bandwidth is adapted from 755KHz to 916KHz in order to adapt range accuracy from 10.06m to 8.38m. The bandwidth adaptation can be implemented using software defined radio (SDR) feature of cognitive radios [1], [8].

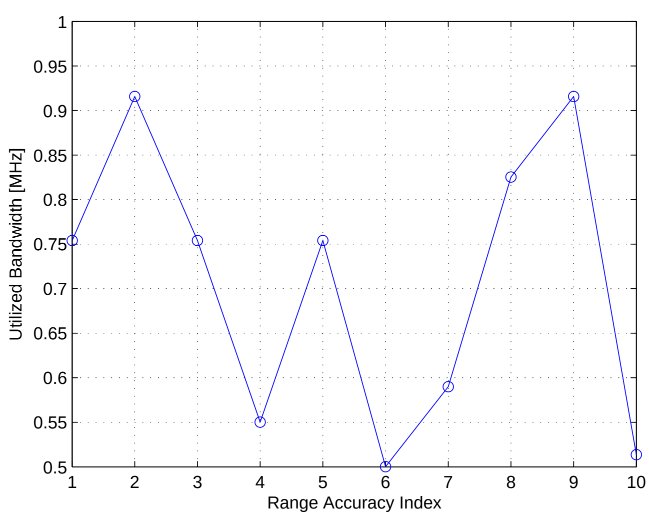

Fig. 5. Bandwidth adaptation in ML-TOA range accuracy adaptation.

Although ML-TOA range accuracy adaptation method is optimal there are some practical limitations. The ML method requires to have complete knowledge of channel parameters (i.e. path amplitude). This is a valid assumption for applications that are performed after channel estimation process. However, it is not a practical assumption for ML-TOA range accuracy adaptation since the channel information is not available yet. Therefore, optimal and suboptimal two step least square (LS) algorithms [9], [10] can be employed to address this issue. For further details on these techniques, we refer the readers to [9], [10].

V. Conclusions

Range accuracy adaptation capability of CR systems is emphasized by inspiring from the range adaptation feature of bats. Performance analysis of ML-TOA range accuracy adaptation is conducted in dynamic spectrum access environment through computer simulations. The results show that ML-TOA estimator can achieve the dynamic range accuracy requirements set by the transmitter with varying but small margins. The results suggest that ML-TOA range accuracy adaptation is a promising underlying method for CR systems to support goal driven and autonomous location aware systems. This study can be extended by developing methods that can reduce the margin between time delay estimator and CRLB.

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