A Modified CA-CFAR Method For LTE Random Access Detection

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***Abstract*—Random Access is an important aspect of mobile systems where multiple users are always competing for resources. However, noise imposes a significant problem to those systems causing them to falsely detect access requests. In consequence, unnecessary processing and air traffic are generated based upon these unreal request events. This paper presents a modified Cell-Average Constant False Alarm Rate (CA-CFAR) strategy used for random access detection of CAZAC preambles in the presence of noise. Simulation results indicate that the proposed method performs well even in the case of low SNR.**

Keywords—CA-CFAR, CAZAC, LTE, PRACH, Random Access Preamble Detection, Zadoff-Chu Sequence.

I. INTRODUCTION

The Random Access Channel (RACH) in Long Term Evolution (LTE) systems is mainly used for User Equipment (UE) to request resources from Base Station (BS) [4]. In the physical random access channel (PRACH) Zadoff-Chu (ZC) sequences are adopted as preambles. This adoption is based on the fact that the ZC sequences present ideal auto-correlation and cross-correlation properties [1-3]. Different ZC sequences or the same ZC sequence with different cycle shifts are used for generating preambles by different User Equipment (UE) [5, 6].

When detecting random access requests from users in a mobile network, a Random Access Detector has the task to determine if a request(s)-plus-noise or only noise is present in the collected data. A RACH detector generally determines if an access to the network is been requested based upon statistical computations. The results from this statistical analysis are employed to calculate a threshold value that is then used to decide whether there is a user requesting access or not. The threshold must be selected carefully once it dictates both the probability of false alarm and the probability of detection [10].

A threshold that achieves a good trade-off between false alarm rate and detection rate, i.e., low false alarm rate and high detection rate, is of extreme necessity for signal detectors. However, there are cases where the lack of statistics on the channel turns the estimation of the noise variance a crucial question to be solved. There are in the literature some techniques that aim at reducing the uncertainty of the noise variance [12]. Among the most important ones is the Cell-Averaging Constant False-Alarm Rate (CA-CFAR) method.

Some CA-CFAR based detectors are proposed in [13, 14]. These detectors are basically divided into two phases. The first phase, known in the literature as censoring, finds among the collected data a set of uncorrupted cells (samples) which are later used as reference cells. The second phase performs the actual detection procedure.

Constant false alarm rate (CFAR) strategies can be effectively employed in cases where the noise statistics are generally unknown, which is true for wireless channels. In those cases, the detection threshold is found through the use of signal-free sets of samples, which are called reference sets. The majority of CA-CFAR detectors calculate the threshold as being the sum of the squared reference set, which is then multiplied by a scaling factor [7]. The scaling factor has a direct relation to the desired probability of false alarm.

In this paper, a modified version of the CA-CFAR method is presented and assessed. It is employed for detecting the presence of preamble sequences in the random access channel. The remainder of this work is organized as follows. Section II briefly describes the structure of the LTE signal. Section III introduces both the PRACH receiver structure adopted for user detection and the energy measurement the proposed method relies on. In Section IV, a modified version of a CA-CFAR detector is proposed. Results are showed and discussed in Section V. Finally, Section VI presents the conclusions.

II. LTE SIGNAL STRUCTURE

The LTE standard adopts a multicarrier approach in order to reach data rates as high as 300 Mbps in the downlink and 170 Mbps in the uplink. In the downlink, Orthogonal Frequency Division Multiple Access (OFMDA) is adopted as the modulation scheme and in the uplink, Single Carrier - Frequency Division Multiple Access (SC-FDMA) is the modulation scheme employed. The standard defines bandwidths ranging from 1.25 MHz up to 20 MHz. Highly efficient modulations such as 64QAM are also part of the standard [8].

A. LTE Generic Frame Structure for FDD

Figure 1 shows the LTE Generic Frame Structure for Frequency Domain Duplexing (FDD). As can be seen, LTE frames are 10 [ms] long. They are divided into 10 sub-frames where each sub-frame is 1.0 [ms] long. Each sub-frame is further split into two slots, each one being 0.5 [ms] long. Slots consist of either 6 or 7 ODFM symbols, depending on whether the normal or extended cyclic prefix is employed [9].

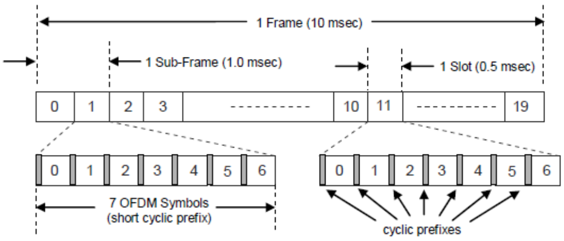

Fig. 1. LTE Frame Structure for FDD Systems.

B. Random Access Channel and Preamble Sequence Generation

The RACH is an uplink transport channel employed in initial network random access by an UE. The RACH channel is carried by the PRACH channel. The main purpose of the random access procedure is to obtain both uplink time synchronization and access to the network for a given UE.

The Physical Random Access Channel (PRACH) preamble, illustrated in Figure 2, consists of a Cyclic Prefix (CP) of length T_{CP} and a sequence part of length T_{PRE}.

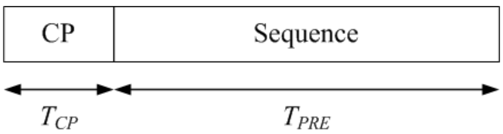

Fig. 2. Random Access Preamble Format.

Prime-length Zadoff-Chu (ZC) sequences are adopted as random access preambles in LTE systems due to its Constant Amplitude Zero Auto Correlation (CAZAC) properties [1, 2], i.e., all points of the sequence lie on the unit circle and its auto-correlation is zero for all time shifts other than zero. These properties make Zadoff-Chu Sequences very useful in channel estimation and time synchronization and also improve PRACH detection efficiency [10].

The PRACH sequence, which is normally 800 [μs] long, is created by cyclically-shifting a ZC sequence of prime-length N_{ZC}, defined as [5]:

$$x_u(n) = \exp\left[-j\frac{\pi u n(n+1)}{N_{ZC}}\right], \quad 0 \le n \le N_{ZC} - 1 \qquad (1)$$

where u is the ZC sequence index, n is the time index and the sequence length $N_{ZC} = 839$ for FDD systems [5]. The PRACH has a bandwidth of 1.08 MHz that is equivalent to 6 Resource Blocks (RB). It uses a subcarrier spacing of 1250 Hz for preamble formats 0 - 3 [5]. The N_{ZC} preamble subcarriers are specifically positioned in the center of the 1.08 MHz bandwidth so that there is a guard band of 15.625 KHz on each side of the preamble. Figure 3 depicts the PRACH preamble structure in the frequency domain according to what was just exposed.

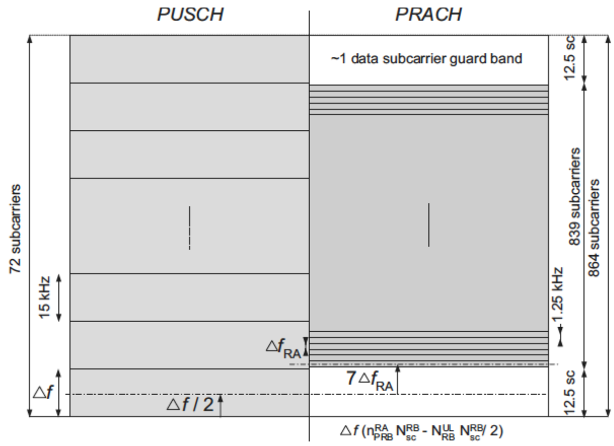

Fig. 3. Preamble mapping onto allocated subcarriers [10].

From the uth root ZC sequence, random access preambles with zero correlation zones of length N_{CS} - 1 are defined by cyclic shifts according to:

$$x_{u,v}(n) = x_u\big((n + C_v) \bmod N_{ZC}\big) \qquad (2)$$

where N_{CS} gives the fixed length of the cyclic shift, v is the sequence index and Cv is the cyclic shift applied to the root ZC sequence. These parameters are defined in [5].

III. PRACH RECEIVER

In order to reduce, i.e., simplify, the number of multiplications performed by the PRACH detector at eNodeB, a frequency domain processing approach is chosen for the preamble detection [10]. First, the captured signal is preprocessed in time domain, next it is translated to the frequency domain by the FFT block and multiplied with the Fourier transformed RACH sequence. The cross correlation is obtained by transforming the multiplication result back to time domain, which is performed by the IFFT and zero-padding blocks. Figure 4 describes the main components of the RACH preamble detector, using a DFT-based (frequency-domain) SC-FDMA receiver [11].

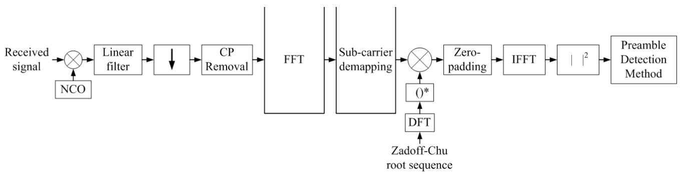

Fig. 4. RACH preamble SC-FDMA receiver structure.

The first block in Figure 4 represents a down-converter, which shifts the PRACH pass-band signal to base-band. After down-converting the signal, the linear filter is applied in order to avoid aliasing after decimation. The result of the decimation block is fed into the CP removal block. After removing the Cyclic Prefix, the FFT engines transform the SC-FDMA symbols from time domain into frequency domain. The sub-carrier de-mapping block extracts the RACH preamble sequence from the output of the FFT engine. The result of sub-carrier de-mapping is multiplied by the ZC root sequence and then fed into a zero-padding block. Finally, the IFFT engine transforms the cross-correlation result from frequency domain into time domain. The energy detection block estimates noise power, sets the detection threshold and then decides if a preamble is present. For further information on this receiver, refer to [10].

A. Power Delay Profile Computing

Frequency-domain periodic correlation is an efficient method that can be used by the PRACH receiver in order to compute the Power Delay Profile (*PDP*). Through the use of it the PDP of the received sequence can be found by:

$$PDP(l) = |z_u(l)|^2 = \left|\sum_{n=0}^{N_{ZC}-1} y(n) x_u^*\left[(n+l)_{N_{ZC}}\right]\right|^2 \quad (3)$$

where $z_u(l)$ is the discrete periodic correlation function at time lag l between the received sequence $y(n)$ and the locally generated root ZC sequence $x_u(n)$ where $(.)^*$ denotes the complex conjugate. Both sequences are of length N_{ZC}. It is worth noticing that by making use of the properties of the DFT, $z_u(l)$ can efficiently be computed in the frequency domain.

Unique preambles are generated by cyclically shifting a given ZC root sequence. As a direct consequence, the *PDP*, which is expressed by equation (3), produces with only one single calculation all preambles generated from the same ZC root sequence [10]. Consequently, preambles are detected simply by looking for *PDP* samples which values are higher than a pre-defined threshold. This search procedure is performed along a set of *PDP* samples corresponding to the cell size.

IV. Proposed Preamble Detection Method

The energy measurement and the collected data processing are performed in base-band by a device with the architecture depicted in Figure 4. The detection method proposed here is carried out in two stages making use of the PDP samples.

The preamble detection procedure consists basically of hypothesis tests following the Neyman&Pearson lemma [17]. This lemma establishes that detectors based on likelihood ratio tests:

$$\frac{\mathrm{PDP}_{\mathrm{H_1}}}{\mathrm{PDP}_{\mathrm{H_0}}} > \gamma \quad (4)$$

where the hypothesis H_0 is rejected in favor of H_1 when the desired signal (preamble) is present, is optimum when the cumulative distribution function (CDF) of this ratio given the hypothesis H_0 is known, so that it is possible to calculate the threshold that satisfies

$$P\left\{\frac{PDP_{H_1}}{PDP_{H_0}} > \gamma \mid H_0\right\} = P_{FR} \quad (5)$$

for a given false rejection probability P_{FR}. Typically, the derivation of this function assumes the knowledge of the probability distribution function of both random variables PDP_{H_1} and PDP_{H_0}.

The method proposed in this paper is composed of two stages. The first stage is used to identify PDP samples that can be considered as containing only the presence of noise, i.e., energy samples, which better represent the hypothesis H_0. These energy samples must be identified in order to calculate the decision threshold γ of the hypothesis test in the next stage.

The next stage makes use of both the decision threshold γ and the energy of the reference samples to test each one of the PDP samples. This procedure makes it possible to reliably decide if there is signal being transmitted on the PRACH channel.

A. Censoring Algorithm

The censoring algorithm adopted in this paper is known as Forward Consecutive Mean Excision (FCME) [16]. The basic principle of the algorithm consists in sorting the PDP samples in ascending order of energy.

$$\{\mathrm{PDP(i)} \mid \mathrm{i} = 0,1, \dots, \mathrm{N_{ZC}} - 1\} \quad (6)$$

which results in the ordered set:

$$\{\mathrm{PDP}^{(\mathrm{i})} \mid \mathrm{i} = 0,1, \dots, \mathrm{N_{ZC}} - 1\} \quad (7)$$

where,

$$PDP^{(0)} < PDP^{(1)} < PDP^{(2)} < \cdots < PDP^{(N_{ZC}-1)} \quad (8)$$

Then it discards all samples with energy greater than $\mathrm{PDP}^{(\mathrm{I})}$ such that:

$$PDP^{(I)} > \tau_I \sum_{i=0}^{I-1} PDP^{(i)} \quad (9)$$

where τ_{I} is the censoring scaling factor at the Ith step.

The algorithm used to search for $PDP^{(I)}$ is performed iteratively, being necessary to calculate the censoring scaling factor τ_{I} for each iteration. The scale factor calculation is done under the initial assumption that $PDP^{(I)}$ is a PDP sample that only contains noise, i.e., free of the presence of signal. Under this assumption, the probability that this test is true corresponds to a probability of false disposal P_{FD} given by

$$P_{FD} = P\left\{PDP^{(I)} > \tau_I \sum_{i=0}^{I-1} PDP^{(i)} \mid H_0\right\} \quad (10)$$

where P_{FD} is a predefined constant. For the first iteration *I* should be made equal to a number corresponding to the smallest possible set of clean *PDP* samples. It is normally made equal to 25% of the entire set [15]. The parameter *I* keeps increasing at each iteration until the condition in eq. (9) is true or it reaches the last sample of the set, meaning that the *PDP* set is signal-free, i.e., it contains only noise samples.

As the quadrature components of the correlation signal $z_u(l)$ present Gaussian distribution with zero mean and variance equal to $N_{ZC}\sigma^2/2$, the PDP samples, consequently, present a non-central Chi-squared distribution with 2 degrees of freedom and mean given by [10]

$$E\left[PDP^{(i)}\right] = N_{ZC}\sigma^2 \quad (11)$$

Equivalently, each PDP sample presents an exponential distribution that is a special case of the Chi-square distribution. Furthermore, since:

$$\sum_{i=0}^{I-1} PDP^{(i)} \simeq I\, \mathrm{E}\left[PDP^{(i)}\right] \quad (12)$$

Then the equation for the probability of false disposal P_{FD} can be approximated by:

$$P_{FD} = P\left\{PDP^{(I)} > \tau_I\, I\, N_{ZC}\sigma^2\right\} \quad (13)$$

This approach becomes better as the set of reference samples I increases. Therefore, the probability of false disposal P_{FD} can be approximated by:

$$P_{FD} = e^{-\tau_I I} \quad (14)$$

The probability of false disposal P_{FD} is the desired rate at which clean samples, i.e., samples containing only noise, are regarded as signal-plus-noise samples and therefore, discarded. The output of the censoring (disposal) stage is defined by the total energy of the noise reference samples, which is then calculated by:

$$PDP_{ref} = \sum_{i=0}^{I-1} PDP^{(i)} \quad (15)$$

and also by the number of PDP samples I employed to calculate PDP_{ref}.

B. Detection Procedure

After defining the set of reference samples containing only noise, the next stage consists in testing each PDP sample against PDP_{ref}, which is performed through evaluation of the following hypothesis test:

$$PDP(l) \geq \gamma \, PDP_{ref}, \quad \text{for } l = 0, 1, \ldots, N_{ZC} - 1 \quad (16)$$

where γ is the detection threshold which is determined by the decision method employed. Herein the Cell Averaging (CA) method is employed to calculate the detection threshold γ [15].

The detection threshold γ is calculated under the hypothesis of signal absence, i.e., the reference samples contain only noise, for a given probability of false alarm P_{FA} defined as:

$$P_{FA} = P\left\{\frac{PDP(l)}{PDP_{ref}} > \gamma \mid H_0\right\} \quad (17)$$

Once it is assumed that the quadrature components of the PDP have Gaussian distribution, therefore in consequence, the energy measures $PDP(l)$ and PDP_{ref} present non-central Chi-square distribution with 2 (exponential distribution) and $2I$ degrees of freedom, respectively. Given that the ratio between two Chi-square distributions results in a Fisher distribution whose cumulative distribution function is given by:

$$FCDF(\gamma) = 1 - P\left\{\frac{PDP(l)/2}{PDP_{ref}/2I} > I\,\gamma\right\} \quad (18)$$

then the detection threshold γ is calculated by

$$\gamma = FCDF^{-1}(1 - P_{FA}, 2, 2I)/\, I \quad (19)$$

where FCDF is the Fisher Cumulative Distribution Function.

After calculating the detection threshold γ, the decision procedure is carried out by evaluating eq. (16) for all PDP samples. If the test given by eq. (16) is true for a given sample then the hypothesis H_1 is chosen, i.e., a user is requesting access. On the other hand, if the test is false, then hypothesis H_0 is decided to be true, i.e., the sample is signal-free. Figure 5 summarizes the whole process performed by the method previously proposed.

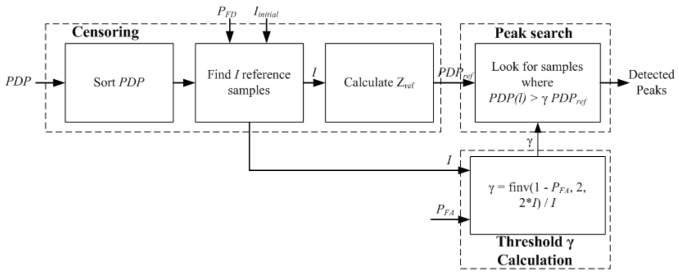

Fig. 5. Preamble detection method.

V. NUMERICAL RESULTS

The threshold given by the method proposed here is found via computer simulations. The number of Monte Carlo trials was greater than 10^5 iterations. The ideal AWGN channel is assumed. During the simulations, a user is said present when the energy of a given PDP sample is greater than the estimated threshold. In this paper, the initial set size for the censoring stage is made equal to 25% of N_{ZC}, which is the reference set.

For the results presented here, the probability of false alarm P_{FA} is made equal to 10^{-4} and the probability of false disposal P_{FD} is made equal to 10^{-3} and therefore, evaluating equation (14) results that the value for $\tau_I\, I = T_{CME}$ is 6.9078.

Figure 5 shows the simulated probability of detection, P_D, for one signature generated from one ZC root sequence when the SNR varies from -30 [dB] up to 30 [dB]. It can be noticed that for SNR values greater than -20 [dB], the probability of correct detection is 1, i.e., the presence of a preamble is always detected.

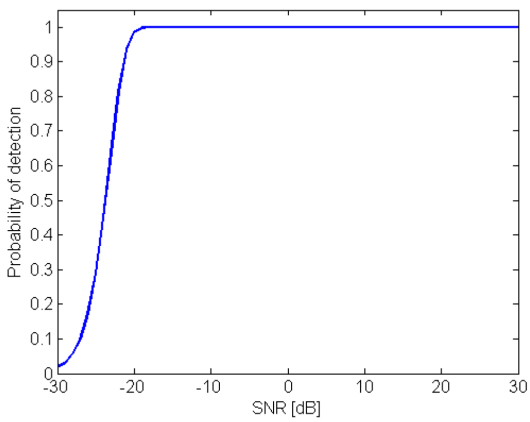

Fig. 6. Simulated detection probability.

Figure 6 depicts the corresponding false alarm probability when the SNR varies from -30 [dB] up to 30 [dB]. Again, only one signature is generated and transmitted. The P_{FA} for each trial is computed over all PDP samples only excluding from the computation the sample that indicates the presence of the transmitted signature. It can be noticed that P_{FA} varies from approximately 1.03 x 10^{-4} up to 1.1 x 10^{-4}, showing that the method keeps P_{FA} close the value set previously for that parameter.

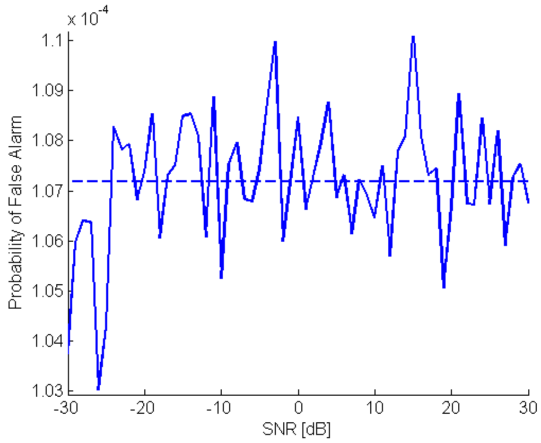

Fig. 7. Simulated false alarm probability.

A comparison between the desired P_{FA}, which is varied from 1 x 10^{-5} up to 1 x 10^{-4}, and the value achieved by the proposed method is presented in Figure 7. As can be noticed, the achieved P_{FA} value stays rather close to the desired one.

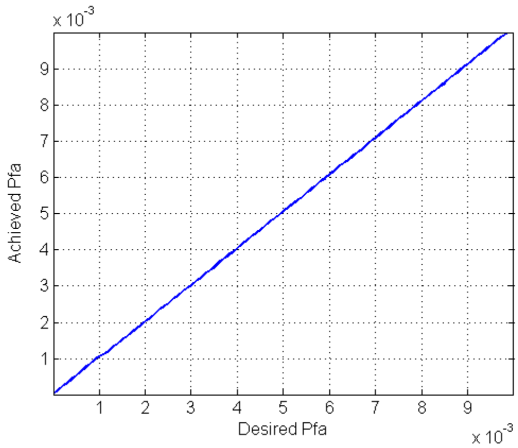

Fig. 8. Comparison between the desired P_{FA} and the actually achieved value, where SNR = 0 [dB].

Figure 8 shows P_D versus P_{FA} (ROC plot). In that figure P_{FA} is also varied from 1 x 10^{-5} up to 1 x 10^{-4} with SNR equal to 0 [dB]. It shows an ideal ROC curve where the presence of a user is always detected independently of the value of P_{FA}.

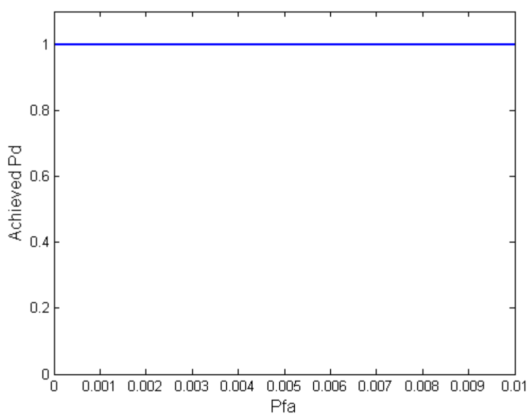

Fig. 9. ROC plot showing P_D versus P_{FA} with SNR = 0 [dB].

The proposed method achieves better performance than the methods presented in [18] and [19], where the probabilities of false alarm, P_{FA}, are 5 x 10^{-3} and 10^{-4} respectively.

The major disadvantage presented by the method is that it is highly time-consuming. MATLAB [20] provides a function called *profile*, which provides users with a way to identify and measure where a program spends most time. Table I presents the results obtained by running the *profile* function with the detection method proposed in Section IV along with the pre-processing receiver functions. The algorithm was executed 1000 times and the total simulation time is 167.381 [s].

TABLE I. PROFILE REPORT

Function name	Time spent [s]	Percentage %
FFT	0.066	0.0394
Subcarrier de-mapping	0.004	0.0024
Multiplication of sequences	0.014	0.0084
PDP Calculation	0.137	0.0818
PDP Sorting	164.032	97.9992
Censoring	2.772	1.6561
Calculate Z_{ref}	0.007	0.0042
Calculate threshold	0.129	0.0771
Find peaks	0.122	0.0729

Through the assessment of the provided data, it is easily noticed that the sorting procedure is a huge bottleneck, consuming more than 97 % of the simulation time. It can also be noticed that the censoring procedure is the second most time-consuming function present in the method. Together, the PDP Sorting and Censoring procedures consume more than 99.5 % of the time necessary for the method to detect the presence of preambles.

This drawback increases the time the method takes to detect the presence of a user and may impose a constraint to both the number of users it can simultaneously detect and the cell size depending on the architecture the method is implemented.

VI. CONCLUSIONS

A modified CA-CFAR method was proposed in this paper. Its main goal is to detect CAZAC sequences that are sent by UEs in order to request the allocation of resources. The numerical results showed that the modified iterative CA-CFAR method proposed here could detect the presence of a user even in the case of SNR as low as -17 [dB]. Also, as the results presented here show that the proposed method does well even in low SNR environments it could be suitable for cognitive radios.

Future work will concentrate on investigations to improve the performance and decrease the computational complexity presented by the proposed method allowing it to be easily implemented in any architecture. Additionally, the influence of the use of antenna diversity over the performance of the method will be assessed as well.

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