Double-Threshold Based Narrowband Signal Extraction

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***Abstract*— A localization algorithm based on double-thresholding (LAD) is a computationally simple method for localizing narrowband signals in the frequency domain. The method does not need any *a priori* information about the narrowband signal. The localization is based on two thresholds. The lower threshold is used to compose adjacent signal samples into clusters whereas the upper threshold is used to detect signals. The LAD can be applied in narrowband signal detection as well as in interference suppression. The simulation results show that the LAD gives quite good localization accuracy and the LAD is able to determine correct number of narrowband signals even over 95% of the cases.**

I. INTRODUCTION

Overlay systems may become common in wireless communications due to the limited amount of frequency bands. In overlay systems, spread spectrum (SS) signals coexist with narrowband (NB) signals used in conventional communication systems. NB signals may also be interference, either natural or artificial. Detection and localization of those NB signals may lead to their mitigation [1] and, as a consequence, improvements in SS system's performance.

New technologies, such as cognitive radio [2], [3], use information about existing signals in order to achieve better use of radio frequencies. Dynamic frequency selection (DFS) [4] means that a free frequency band is searched for and selected before transmitting an information signal. Simple and efficient algorithms are needed for that purpose.

A large number of interference excision or NB signal detection algorithms are based on the use of a threshold. The threshold can be calculated in numerous ways, see, e.g., [5], [6]. Threshold setting is a critical task since the performance of excision or detection algorithm depends on that. Even though the threshold is set properly there exist problems. One problem is that the NB signal energy at a certain frequency within the frequency band of the NB signal may temporarily drop below the threshold. This causes needless separation of the NB signal into two (or more) parts. Also, the noise (and a possible wideband signal) may temporarily yield to threshold crossing and cause falsely detected NB signals. In other words, if the threshold is high, the NB signal may be separated into several parts but false detections are avoided. On the other hand, if the threshold is small, false detections become more common but needless separation of the NB signal is avoided.

Several methods have been proposed for reducing problems mentioned above, e.g., [7], [8], [9], [10]. However, many of these methods either have to have some *a priori* knowledge, e.g., from the noise level, or have high computational complexity. The localization algorithm based on double-thresholding (LAD) has been proposed in [11] by the authors. The LAD thresholds can be calculated with the simple and efficient forward consecutive mean excision algorithm (FCME) [6]. The LAD does not need *a priori* knowledge about the signal to be detected or the noise level, and its computational complexity is relatively low. Herein, the LAD is briefly presented and its performance is studied by means of the correct number of narrowband signals it is able to detect as well as the bit error rate (BER). The latter has not been studied previously.

II. SYSTEM MODEL

The received signal is assumed to have the form

$$r(n) = s(n) + i(n) + w(n), \tag{1}$$

where $s(n)$ is caused by the direct sequence (DS) SS signal, $i(n)$ is a narrowband signal and $w(n)$ is the noise process. Two types of narrowband signals are considered; these are sinusoids and band-limited binary phase shift keying (BPSK) signals.

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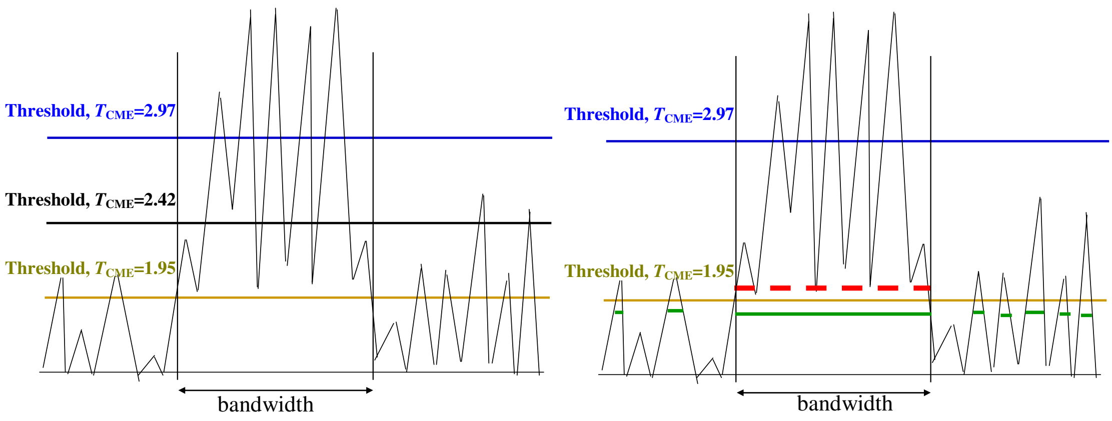

(a) (b)

Fig. 1. A RC-BPSK signal in the frequency domain. (a) The FCME algorithm with threshold parameters 2.97, 2.42 or 1.95. The upmost threshold finds 5 signals, the middle threshold finds 6 signals and the lowest threshold 8 signals. (b) The LAD with upper (threshold parameter 2.97) and lower (threshold parameter 1.95) thresholds. The LAD finds 8 groups (green solid line), i.e., peaks above the lower threshold, but only one group is accepted to be a signal (red dashed line), i.e., if a peak of the cluster exceeds the upper threshold.

III. Localization Algorithm based on Double-Thresholding

Because the threshold calculation of the LAD is analogous to that of the FCME algorithm, the FCME algorithm [6] is presented at first. The FCME algorithm was originally designed for interference suppression (IS), but it can be applied also to NB signal detection. The FCME algorithm is automated method for setting a threshold in order to separate the samples into two sets. The NB signal (above the threshold) consist the extracted NB signal, whereas the wideband signal set (below the threshold) consists the wideband signal and the noise. The threshold is calculated iteratively. The threshold computation uses a threshold parameter which is calculated *a priori* using the statistical properties in the noise-only case and a desired clean sample rejection rate [5], [6]. However, the noise power may be unknown.

The FCME algorithm starts by rearranging the samples in the ascending order according to their energies [6], [12]. The n smallest terms in the sorted set are selected to belong to the initial set assumed to be free of interference (the 'clean set'). The size of the initial set is typically about 10 % of the size of the data set. In that case, the set is usually small enough to be free of interference, and large enough to ensure that the algorithm converges.

The threshold for the FCME algorithm is [5], [6]

$$T_h = \overline{x^2} T_{\mathrm{CME}}, \tag{2}$$

where

$$\overline{x^2} = \frac{1}{Q} \sum_{i=1}^{Q} |x_i| \tag{3}$$

is the average sample envelope of the current set (initially the initial set), Q is the set size and T_{CME} is the threshold parameter. The threshold parameter [5]

$$T_{\mathrm{CME}} = \sqrt{\frac{4}{\pi}} \sqrt{-\ln(P_{\mathrm{FA,DES}})} \tag{4}$$

is obtained assuming that noise-only data has Gaussian distribution. In (4), $P_{\mathrm{FA,DES}}$ is the desired clean sample rejection rate which roughly describes how many samples are above the final threshold in the noise-only case. When the clean sample rejection rate is selected to be 0.1 %, the threshold parameter T_{CME} is 2.97. Correspondingly, with the clean sample rejection rate 1%, the threshold parameter T_{CME} is 2.42 and with the clean sample rejection rate 5% the threshold parameter T_{CME} is 1.95 [5]. It is also possible to use, e.g., sample energies $|x_i|^2$ instead of sample envelopes $|x_i|$. In that case the threshold parameter is [6]

$$T_{\mathrm{CME}} = -\ln(P_{\mathrm{FA,DES}}). \tag{5}$$

In the first iteration the FCME algorithm calculates $\overline{x^2}$ of the initial set. All the samples that are below the threshold T_h are accepted to the set. The FCME algorithm iteratively calculates a new value for $\overline{x^2}$ and a new threshold T_h until there are no new samples below the threshold.

Obviously, the threshold depends on the used threshold parameter. Three thresholds that are obtained using three distinct threshold parameters are presented in Fig. 1(a) as an example. It can be seen that if the threshold is large, the threshold may separate a NB signal into several signals. On other hand, if the used threshold is small, noise components may rise above the threshold and cause falsely detected signals.

In order to avoid these problems, the LAD uses not one but two threshold parameters and, thus, has two thresholds, lower and upper. The lower threshold is used to avoid separating a signal and the upper threshold helps to avoid

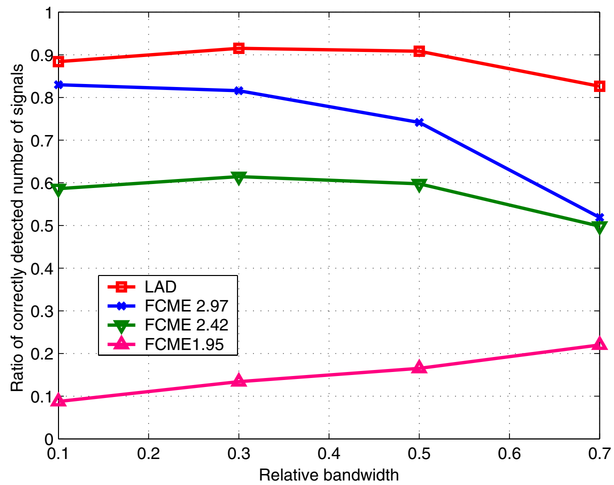

Fig. 2. Number of correctly detected signals vs. relative bandwidth of the RC-BPSK signal. ISR=30 dB.

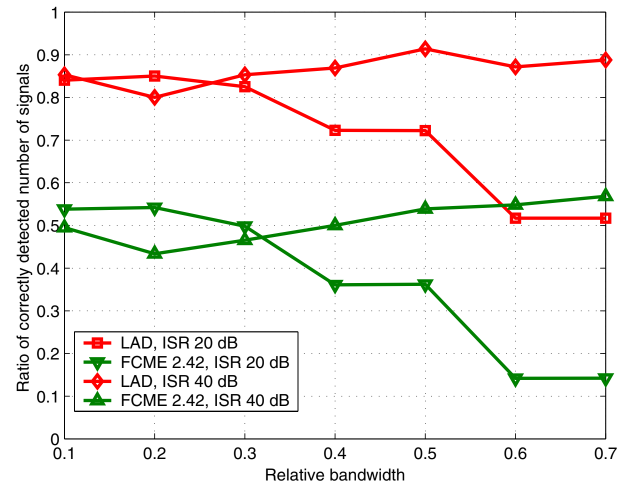

Fig. 3. Number of correctly detected signals vs. relative bandwidth of the RC-BPSK signal.

false detections. The threshold parameters should be selected so that another is large enough and another is small enough. This is a difficult problem. It was noticed in [11] that threshold parameters 1.95 and 2.97 seem to be appropriate. These threshold parameters are obtained using 5% and 0.1% clean sample rejection rates, respectively. After calculating the thresholds with two threshold parameters using the FCME algorithm, the LAD groups the adjacent samples above the lower threshold into the same group, called as a *cluster*. The largest element of a cluster is compared to the upper threshold. If the largest element exceeds the upper threshold, it is decided that the cluster corresponds to a NB signal. If the largest sample is below the upper threshold, the cluster corresponds to the noise and possible wideband information signal. The threshold setting of the LAD is compared to that of the FCME algorithm in Fig. 1(b). The figure demonstrates the advantages of the LAD algorithm.

IV. SIMULATION RESULTS

In the simulations, the wideband signal is a binary phase shift keyed (BPSK) direct sequence (DS) SS signal with 63–chip Gold codes. Sinusoidal signals and bandlimited BPSK communication signals are used as a NB signals. The narrowband BPSK signal was band-limited by a root raised cosine (RC) filter with a roll-off factor of 0.22 [13]. The frequency domain samples were calculated with the windowed 64–point fast Fourier transformation (FFT). A 4-term Blackman-Harris window was used to reduce the spectrum leakage. It should be noticed that the windowing loss caused by this window is about 3 dB [14]. The DS-signal-to-noise ratio (SNR) per bit was set to 15 dB and the NB-to-DS-signal ratio (ISR) to 30 dB per NB signal unless otherwise mentioned. The FCME threshold parameter was 1.95, 2.42 or 2.97 and the LAD threshold parameters were 1.95 (lower threshold) and 2.97 (upper threshold) [5], [6].

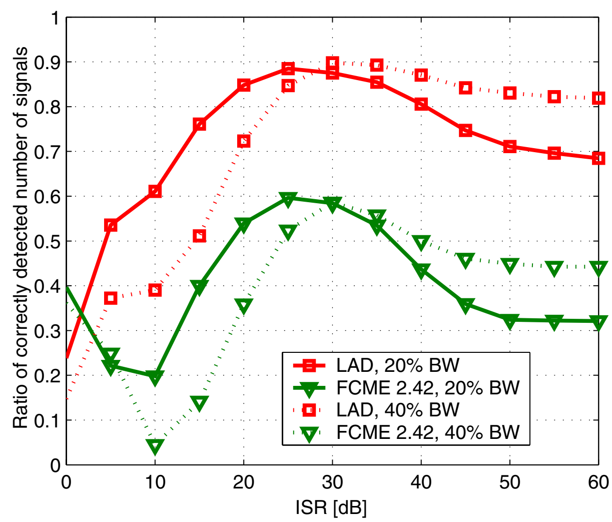

Fig. 4. Number of correctly detected signals vs. ISR, with RC-BPSK signal.

Although the LAD was used on the Fourier domain, it may be used also in other domains, e.g., in time domain.

Figs. 2 – 4 present the ratio of correctly detected number of signals as a function of relative bandwidth or ISR in RC-BPSK signal case. The number of NB signals is one. In Fig. 2, the LAD and the FCME algorithm with three threshold parameters are compared. It can be observed that the LAD outperforms the FCME algorithm. The LAD is able to find the correct number of signals (which is one) even over 90% of the cases. It should be noticed that even though the performance of the FCME algorithm with threshold parameter 2.97 is rather good, its bandwidth estimation success rate is poor. In Fig. 3, ISR 20 dB and 40 dB are also considered. In Fig. 4, RC-BPSK signal with 20% and 40% relative bandwidth is studied. The performance of the LAD is better than that of the FCME algorithm. The performance of the LAD is even excellent when ISR is about 30 dB.

Fig. 5 presents the bandwidth estimation success rate vs. relative bandwidth of the RC-BPSK signal. It is assumed that the signal is detected correctly, i.e., number of detected signals is one. When the bandwidth of the signal is wide enough, the LAD is able to determine the bandwidth of the signal rather well. With large ISR, rising sidelobes make the signal wider and cause some performance loss, especially when the bandwidth of the signal is narrow.

Figs. 6 and 7 illustrates the number of correctly detected sinusoidal signals as a function of ISR and SNR, respectively. The number of sinusoidal signals is three. Two constant separations between the sinusoidal signal center frequencies were used. These were 15% and 30% of the system bandwidth. In both the cases, the LAD outperforms the FCME algorithm. With 30% separation, the performance of the LAD is excellent. The LAD is able to determine the correct number of signals even in 95% of the cases. By comparison, the FCME algorithm is able to find correct number of signals at most in 60% of the cases. With 15% separation and large ISR, the sinusoidal signals blend together causing some performance loss. When ISR is 40 dB or larger, the performances of the LAD and FCME algorithm collapse. With 30% separation, performance degradation does not occur.

Figs. 8 – 10 compares the uncoded BER performance of the LAD and FCME algorithm. In Fig. 8, results for RC-BPSK signal case are presented and in Figs. 9 and 10, sinusoidal signal case is studied. It can be seen that in both the cases, the performance of the LAD is almost equal than that of the FCME algorithm with threshold parameter 2.42. The FCME algorithm with threshold parameter 2.97 outperforms the LAD. However, it should be noticed that when BER is 10^{-3} or smaller, transmission is in practice error free when a sufficient channel coding scheme is used. In RC-BPSK signal case, the BER performance starts to degrade when ISR is 35 dB or larger. In sinusoidal signal case, the BER performance degrades right after ISR is 50 dB or larger.

The LAD is a blind method and its computational complexity is relatively low. Although the LAD has many good properties, there are some problems. The LAD is not always capable to separate two adjacent signals and it is not able to localize weak signals accurately. In addition, high sidelobes cause problems when estimating the bandwidth of a signal.

V. CONCLUSIONS

In this paper, the localization algorithm based on the double-thresholding (LAD) was investigated in the Fourier domain. The algorithm uses two thresholds to decide are the samples caused by a narrowband signal or not. Considered narrowband signal types were sinusoids and bandlimited communication signals. In both narrowband signal scenarios, the ratio of correctly detected number of signals was evaluated via simulations. In both narrowband signal scenarios the LAD outperformed the FCME algorithm. The LAD was able to determine the correct number of narrowband signals even in 95% of the cases. Also some bit error rate results were presented. The bit error rate performance was same than that of the FCME algorithm or slightly worse, depending on the threshold parameter used in the FCME algorithm.

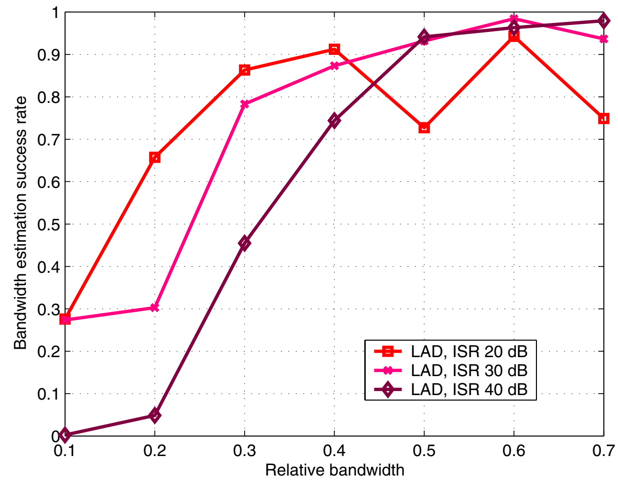

Fig. 5. Bandwidth estimation success rate (assuming correctly detected signal) vs. the relative bandwidth of the RC-BPSK signal.

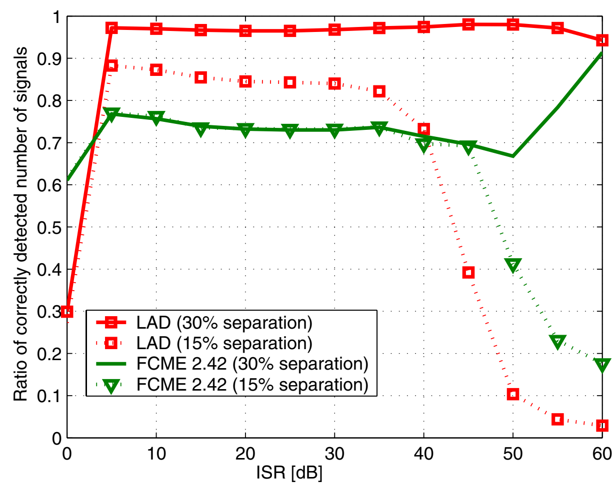

Fig. 6. Number of correctly detected signals vs. ISR, with three sinusoidal signals.

VI. ACKNOWLEDGEMENT

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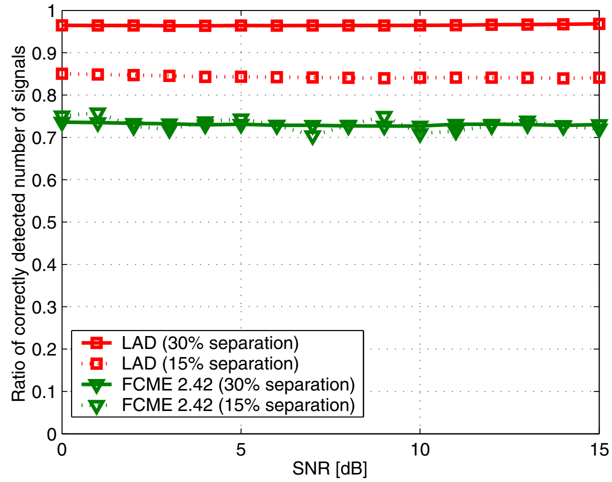

Fig. 7. Number of correctly detected signals vs. SNR, with three sinusoidal signals.

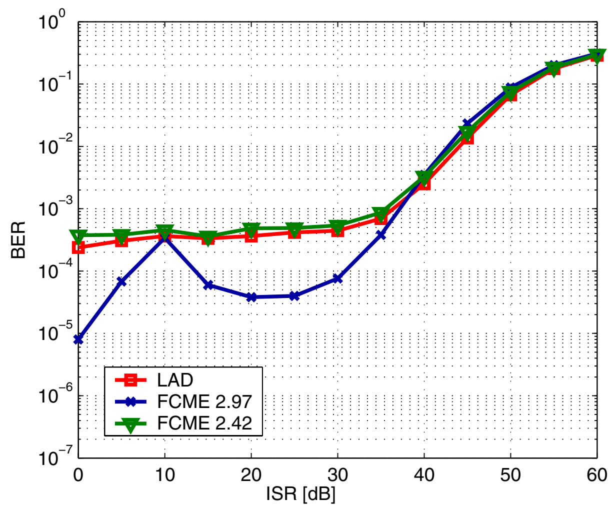

Fig. 8. BER vs. ISR, with RC-BPSK signal. Relative bandwidth is 20%.

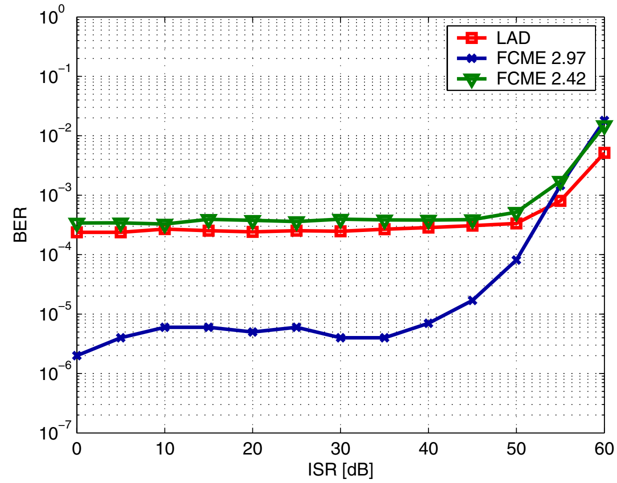

Fig. 9. BER vs. ISR, with one sinusoidal signal.

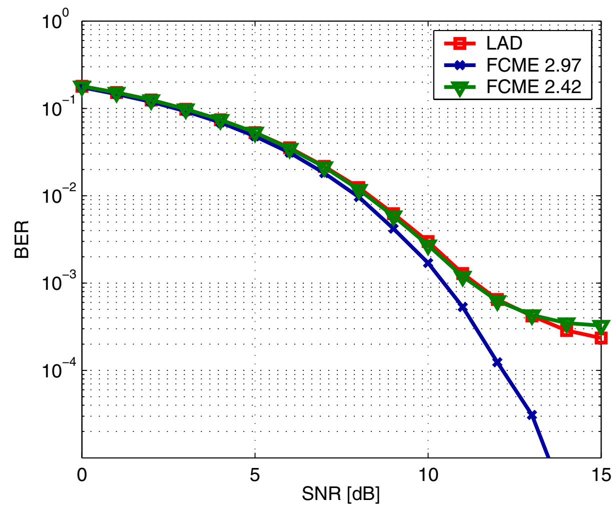

Fig. 10. BER vs. SNR, with one sinusoidal signal.

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