SPECTRUM SENSING WITH LAD-BASED METHODS

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ABSTRACT

Opportunistic spectrum usage would enable enhancing the efficiency of existing and emerging wireless communication systems. One of the key issues related to those systems is spectrum opportunity estimation. In this paper, we are using a technique utilized earlier in narrowband signal detection, namely the localization algorithm based on double-thresholding (LAD), for sensing the existence of primary user signals in a cognitive radio systems. The LAD method requires no *a priori* information on the primary user statistics and it has a low computational complexity that will enable a low-cost real-time implementation. The LAD method is able to estimate the number of narrowband signals and their characteristics, including bandwidth and power. A simplified version of the LAD method which uses normalized thresholds (NT) as well as an enhancement of the scheme that uses adjacent cluster combining (ACC) are proposed. Simulation results show that the simplified version of the LAD method is useful in the considered situations, and the enhanced version of the LAD method improves the performance of the LAD and LAD NT methods significantly.

I. INTRODUCTION

The usage of frequency spectrum in existing commercial systems is inefficient. In the future, the frequency spectrum should be utilized more efficiently. The so called opportunistic spectrum usage [1] techniques are being considered as a solution to this problem. Utilization of unused frequency bands, i.e., spectrum 'white spaces', leads to different spectrum sharing concepts. Therein, secondary (unlicensed) users are allowed to use temporarily unoccupied frequencies if they do not interrupt the primary (licensed) users. That is, the secondary users have to sense the spectrum to find unoccupied channels. Spectrum sharing releases valuable spectrum resource into more effective use by allowing transmission also for secondary users. Main concepts for spectrum sharing are underlay ultra wideband (UWB) transmission [2] and overlay cognitive radio transmission [1], from which the latter one is of our interest herein.

In cognitive radios, which are part of cognitive communication system, a secondary user is allowed to overlay unused frequency bands if it does not cause harmful interference to the primary users. Especially television (TV) bands have been concerned. In [3], the Federal Communications Commission (FCC) proposed to allow unlicensed operation in the TV spectrum at locations where the spectrum is unused. Possible channels for cognitive radio operation are, for example, TV-broadcasting bands at 400-800 MHz. IEEE has formed 802.22 [4] working group which develops cognitive radio based Wireless Regional Area Network especially for use in rural areas. Therein, locally unused TV bands are used for transmission. In [5], a fast Fourier transformation (FFT) based sensing method is presented for detecting narrowband (NB) Part 74 devices, e.g., wireless microphones, in TV bands.

Secondary users need, for example, spectrum sensing [6] in order to select available frequency bands via identifying primary users based on the knowledge of signal characteristics. There exist numerous methods for primary user detection and parameter estimation. Conventional energy detection [7] is non-coherent and, thus, low-complex but has problems with low signal-to-noise ratio (SNR) values. Cyclostationary feature detector [8] has better performance but its computational complexity is higher. For example, TV signals have primary features at cycle frequencies that are multiples of the TV signal horizontal line-scan rate [8]. In [9], partial-matched filtering is used which means that active channels are found via estimating some transmission parameters such as bandwidth (BW) and center frequency of the signals present and comparing this information to the *a priori* broadcast or known transmission parameters. Thresholding with hysteresis [10] would also be applicable for spectrum sensing purpose. Therein, depending on the value of the previous sample, a reduced or increased threshold is used to detect signals. In addition to sensing, occupied channels can be avoided by using, for example, a geolocation and database or beacons [11].

The localization algorithm based on double-thresholding (LAD) method [12–14] could also be applied for finding and localizing NB signals. The localization information that the LAD method gives could be applied in fractional bandwidth use or to identify the subcarriers of OFDM signal as in spectrum pooling. The LAD method is a blind NB signal detection method so no information about the noise level nor NB signals are required. Instead, the LAD method is based on an assumption that the noise is Gaussian. Although this is not the case in practice, it has been noticed that the LAD method is able to operate even though the noise is not simulated Gaussian but from real-life radio channel measurements [14, 15].

The aim of this paper is two-fold: the computational complexity of the basic LAD method is reduced and the performance of the scheme is improved. A simplified version of the LAD method is proposed and studied, namely the LAD with normalized thresholds (LAD NT) method. The LAD NT method is able to reduce the computational complexity without performance loss. The enhanced version of the LAD method, namely the LAD with adjacent cluster combining (LAD ACC), is also proposed. The LAD ACC method is able to estimate the number of NB signals more accurately than the original

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scheme without increasing the computational complexity. The detection performance and BW estimation accuracy are studied via computer simulations.

II. System Model

The received discrete-time signal samples are assumed to have the basic form

$$r(n) = \sum_{k=1}^{m} i_k(n) + w(n), \tag{1}$$

where m is the number of unknown NB signals, $i_k(n)$ is the kth NB signal, and $w(n)$ is a zero-mean complex proper Gaussian random variable with total variance $2\sigma^2$. The noise variance is assumed to be unknown. The considered NB signals are binary phase shift keying (BPSK) communication signals. The signals are assumed to be independent of each other. Although only BPSK signals are considered, corresponding results can be achieved when using other NB signals that have a similar-type spectra, for example, quadrature PSK (QPSK) or 16-QAM (Quadrature Amplitude Modulation) signals.

III. Localization Algorithm Based on Double-Thresholding

The LAD is an adaptive two-threshold based NB signal detection method [12–14]. The usage of two thresholds provides NB signal separation and localization. Usually, the upper and lower thresholds are calculated using the FCME algorithm [16–18]. The FCME algorithm performs the threshold calculation iteratively. The magnitude-squared frequency domain samples $|x_i|^2$ are rearranged in an ascending order according to their sample energies. The complexity of sorting depends on the used sorting method, for example, for Heapsort it is $N \log_2 N$, where N is the number of samples [19]. The threshold parameter T_{CME} is selected. The threshold parameter depends on the distribution of the noise, and in this chi-squared case it is $T_{\mathrm{CME}} = -\ln(P_{\mathrm{FA,DES}})$, where $P_{\mathrm{FA,DES}}$ is the desired clean sample rejection rate, for example, 0.01 (1%) [17]. Note that the noise variance does not need to be known because it has no impact on the threshold setting. The clean initial set Q is selected, usually it includes 10% of the smallest samples.

Step 1: Calculate the threshold [17]

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

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

Step 2: Add all the samples below the threshold to the set Q.

In the first iteration, $\overline{x^2}$ is the mean of the initial set. Next, the set Q is updated, and steps 1 and 2 are performed as long as there are no new samples below the threshold.

To get the two LAD thresholds, the FCME algorithm is run twice with two different threshold parameters T_{CME}, which are called the upper (T_1) and lower (T_2) threshold parameters, $T_1 > T_2$, to get two thresholds T_h, which are called the upper (T_{u}) and lower (T_{l}) thresholds. After the thresholds have been calculated, the LAD method clusters the adjacent samples above the lower threshold T_{l} into the same cluster. The cluster is accepted to be caused by a NB signal if and only if at least one of the samples (the sample with the largest energy) in each cluster is also above the upper threshold. Hence, one accepted cluster corresponds to one detected signal.

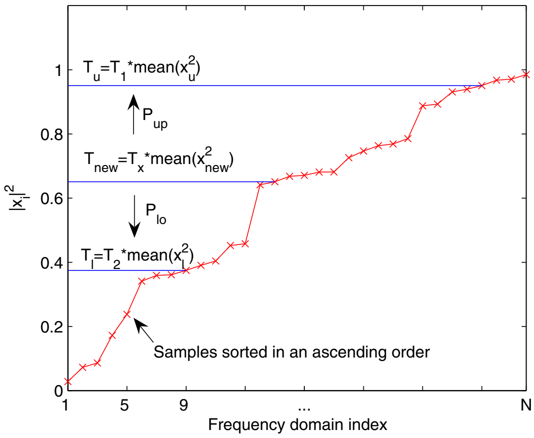

Figure 1: LAD with normalized thresholds (LAD NT). As the original LAD method calculates the upper (T_{u}) and the lower (T_{l}) thresholds separately, the LAD NT method calculates only one threshold, T_{new}, and constitutes the corresponding upper and lower thresholds by multiplying the threshold T_{new} by P_{up} and P_{lo}.

A. *LAD with normalized thresholds*

Originally, the two LAD thresholds are calculated separately. This means that the threshold calculation has to be performed twice. Herein, the threshold calculation is simplified. The threshold is calculated only once using some threshold parameter T_x and after that, some proper coefficients are used to get the required two thresholds. The LAD NT method is illustrated in Fig. 1.

Let us assume that when calculating the thresholds in a traditional way, i.e., two times with two different threshold parameters, the used threshold parameters are T_1 (upper) and T_2 (lower). Instead, the LAD NT method calculates the threshold only once, using only one threshold parameter T_x. The threshold parameter T_x is selected so that $T_2 \leq T_x \leq T_1$. As a result of the iterative calculation, we will get the last threshold $T_{\mathrm{new}} = T_x\overline{x^2_{\mathrm{new}}}$, where $\overline{x^2_{\mathrm{new}}}$ denotes the mean after the last iteration. Now, we will constitute the upper T_{u} and lower T_{l} thresholds

$$T'_{\mathrm{u}} = T_{\mathrm{new}}P_{\mathrm{up}} \tag{3}$$

and

$$T'_{\mathrm{l}} = T_{\mathrm{new}}P_{\mathrm{lo}}, \tag{4}$$

where $P_{\mathrm{up}} = (T_1/T_x)a$ and $P_{\mathrm{lo}} = (T_2/T_x)b$, where $a \geq 1$ and $b \leq 1$ are fixing coefficients defined next.

Coefficients a and b are required to correct the difference between the signal sample mean values. For example, the upper threshold is $T_u = T_1\overline{x^2_u}$ (2) after the original LAD method and $T'_{\mathrm{u}} = T_1\overline{x^2_{\mathrm{new}}}a$ (3) after the simplified LAD NT method. Without coefficient a, $\overline{x^2_u} = \overline{x^2_{\mathrm{new}}}$ which is not the case in practice:

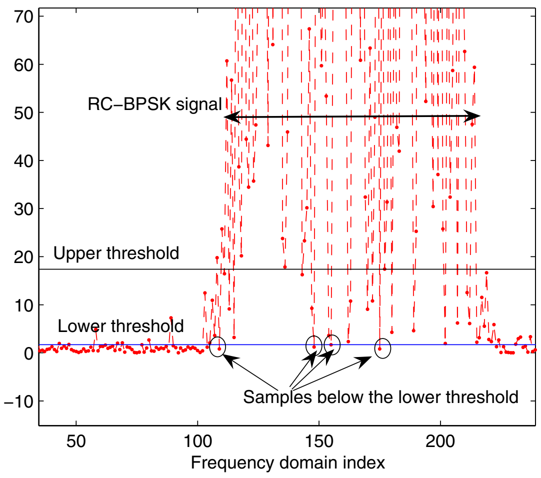

Figure 2: One simulated RC-BPSK signal with BW 10% and SNR 10 dB. The original LAD method separates the signal into 5 parts because of single signal samples that fall below the lower threshold during the signal. Instead, the LAD ACC method does not separate the signal.

the threshold with a larger threshold parameter includes more samples, and because the samples are sorted in an ascending order according their energies, the mean of the set with more samples is larger than the mean of the set with less samples [17]. Then, a proper choice for a is $a = \mathrm{E}[\overline{x_u^2}/\overline{x_{\text{new}}^2}]$, where E is the expectation operator. From (2) and (4), $b = \mathrm{E}[\overline{x_l^2}/\overline{x_{\text{new}}^2}]$. Note, that when using the LAD NT method, the means $\overline{x_u^2}$ and $\overline{x_l^2}$ are unknown. Herein, a and b were selected to be the statistical means in extensive computer simulations with several sinusoidal and BPSK signals. Because the means depend on the actual realizations, T_{u} and T'_{u} – and respectively T_{l} and T'_{l} – do not exactly correspond to each other. However, they are close enough as confirmed with simulations. In this paper, the threshold parameter T_x was selected in two different ways. In case (a), the lower threshold parameter T_2 is used as a threshold parameter T_x, so the threshold T_{new} corresponds exactly the lower threshold of the original LAD method. In case (b), the used threshold parameter T_x is in the middle of the upper and lower threshold parameters, i.e., $T_x = (T_1 + T_2)/2$.

B. LAD with adjacent cluster combining

The original LAD method has problems when estimating the correct number of BPSK signals. Occasional signal components may fall below the lower threshold thus causing separation of the signal as illustrated in Fig. 2. This problem occurs especially when the BW of the BPSK signal is rather wide. This phenomenon can be radically reduced by using the LAD ACC method which uses an extra condition: If accepted clusters are separated by n or less samples below the lower threshold, it is decided that these accepted clusters are caused by one signal. Then, these clusters and these samples below the threshold are joined together. In practice, it means that two different signals can be separated if there are at least $n+1$ adjacent samples between the signals that are below the lower threshold. We

Table 1: The LAD-based NB signal detection methods. T_1 is the upper and T_2 is the lower threshold parameter.

LAD	two-threshold based detection method: T_1, T_2	original
LAD ACC	LAD with adjacent cluster combining: T_1, T_2	enhanced version
LAD NT	LAD with normalized thresholds	simplified version
-case (a)	One threshold parameter, $T_x = T_2$	
-case (b)	One threshold parameter, $T_x = (T_1 + T_2)/2$	

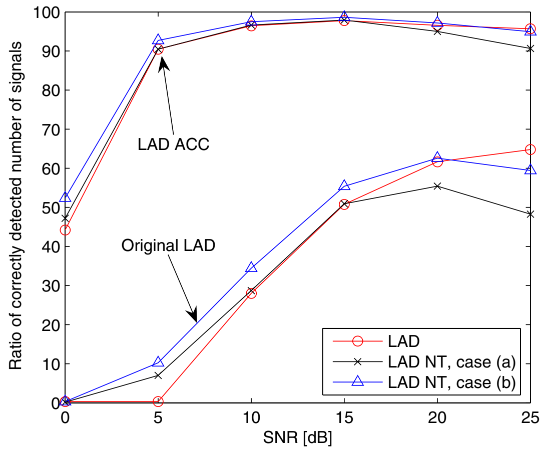

Figure 3: Ratio of correctly detected signals vs. SNR. Two RC-BPSK signals, BWs 5%.

selected herein that $n = 1$.

IV. SIMULATION RESULTS

In the Monte Carlo computer simulations, the original LAD and enhanced LAD ACC methods were studied in the frequency domain. A simplified version of the LAD method, namely LAD NT, was applied to both of these methods. There were complex AWGN channel and 2–4 BPSK signals with relative BWs of 2–10% of the system bandwidth. The SNR values were $0 \dots 25$ dB per signal. The BPSK signals were bandlimited by a root raised cosine (RC) filter with a roll-off factor of 0.22. The number of samples was $N = 1024$, and the FFT length was 1024. There was no windowing.

The LAD threshold parameters were $T_1 = 13.81$ (upper, $P_{\text{FA,DES}} = 10^{-6}$) and $T_2 = 2.66$ (lower, $P_{\text{FA,DES}} = 7 \cdot 10^{-2}$) [12–14]. When using the simplified version of the LAD method, LAD NT, two different cases were investigated. In case (a), the used threshold parameter is the lower original threshold parameter, i.e., $T_x = 2.66$. Herein, $a = 2.1188$, so $P_{\text{up}} = 11$. The upper and lower thresholds are $T'_{\text{u}} = 11T_{\text{new}}$ and $T'_{\text{l}} = T_{\text{new}}$, respectively. In case (b), the used threshold parameter is in the middle of the original threshold parameters, i.e., $T_x = (T_1 + T_2)/2 = 8.235$. In this case, $a = 1.133$ and $b = 0.4489$, so $P_{\text{up}} = 1.9$ and $P_{\text{lo}} = 0.145$. Then, $T'_{\text{u}} = 1.9T_{\text{new}}$ and $T'_{\text{l}} = 0.145T_{\text{new}}$. Herein, six different combinations were studied, namely LAD, LAD NT case (a), LAD NT case (b), LAD ACC, LAD ACC+NT case (a), and LAD ACC+NT case (b), see Table 1.

Figs. 3–6 presents the ratio of correctly detected signals. It presents how often (%) the methods were able to find the cor-

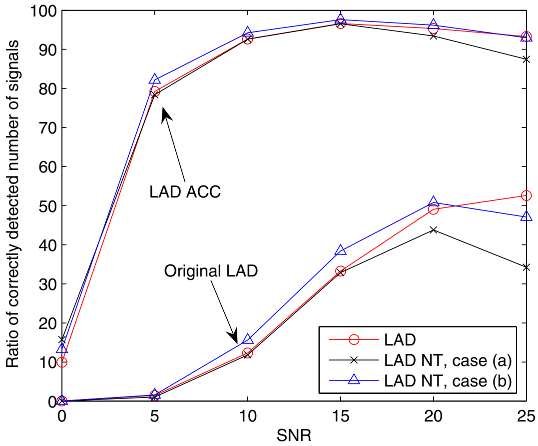

Figure 4: Ratio of correctly detected signals vs. SNR. Two RC-BPSK signals, BWs 7%.

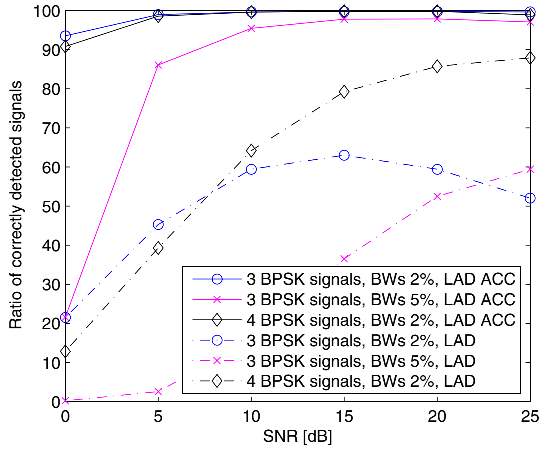

Figure 6: Ratio of correctly detected signals vs. SNR. 3 or 4 RC-BPSK signals, BWs 2 or 5%.

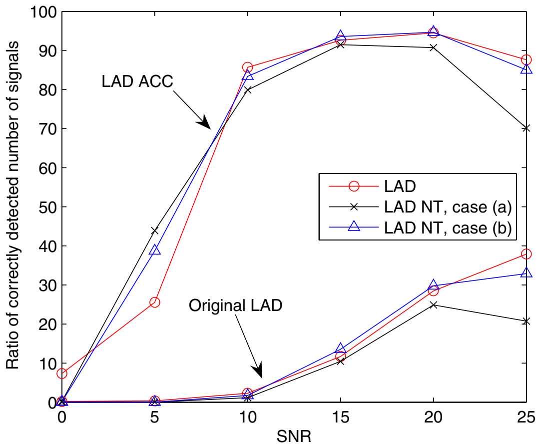

Figure 5: Ratio of correctly detected signals vs. SNR. Two RC-BPSK signals, BWs 10%.

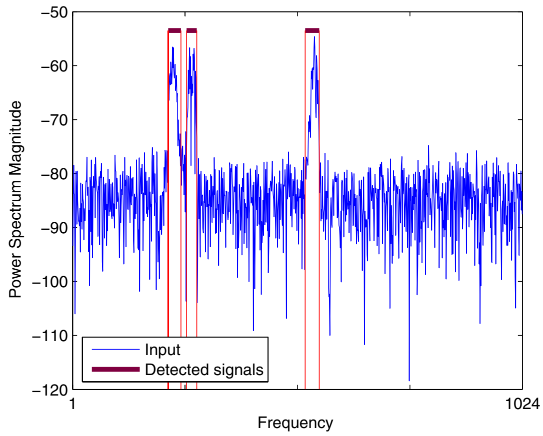

Figure 7: Three RC-BPSK signals with SNR values 5dB. LAD ACC method. Actual BWs 2%, estimated BWs 2.9, 2.3 and 3.2%.

rect number of signals. For example, if the ratio of correctly detected signals is 60%, it means that in 60 % of the cases the method estimated the number of signals correctly. In Fig. 3, there are two BPSK signals with BWs of 5%. It can be seen that the LAD ACC method greatly improves the performance of the original LAD method. Especially at low SNR values, the LAD ACC method offers significantly better performance than the original LAD method. For example, when there are two simultaneous BPSK signals with BWs of 5% and 5 dB SNR, the LAD ACC method estimates the number of signals correctly in 90% of the cases, as the original LAD method estimates the number of signals correctly only in 7% of the cases. This is because when using the original LAD method at low SNR values, occasional signal components may fall below the lower threshold and cause separation of the signal. The simplification (LAD NT) operates well with both the original LAD and LAD ACC methods. However, when SNR is 20 dB or more, LAD NT case (b), in which the used threshold parameter is in the middle of the original ones, offers better performance than LAD NT case (a).

In Fig. 4, the BWs of the two BPSK signals are 7%. The results for the LAD ACC method are almost equal to those in the case when the BWs were narrower. The original LAD method performs worse. Fig. 5 shows the results when the BWs of two BPSK signals are 10%. When SNR is 10...20 dB, the LAD ACC method performs very well. However, the overall performance is worse than that in the previous cases. This is because the overall BW is quite wide. In Fig. 6, there are 3 BPSK signals with BWs of 2 or 5%, or 4 BPSK signals with BWs of 2%. Therein, only results for the LAD and LAD ACC methods are presented. The LAD NT method operates as well as has been shown in previous pictures. The performance of the LAD ACC method is excellent. When the overall BW is narrow, the LAD ACC method operates well even when the SNR is very low.

Bandwidth estimation results are considered in Fig. 7 and in Tables 2–4. Herein, all signal samples that exceed the threshold have taken into account. In Fig. 7, one BW estimation 'snapshot' is presented in the case when there are 3 simultaneous BPSK signals and the LAD ACC method is used. Numerical

Table 2: BW estimation accuracy of LAD ACC.

	Estimated average BWs					
	SNR [dB]					
	0	5	10	15	20	25
2 BPSK signals, BWs 5%	4.9	5.5	5.9	6.6	7.8	9.8
2 BPSK signals, BWs 7%	5.7	7.0	7.6	8.2	9.1	10.4
2 BPSK signals, BWs 10%	1.7	9.4	10.9	11.7	12.4	13.4
3 BPSK signals, BWs 2%	2.3	2.6	3.1	4.1	5.5	7.4
3 BPSK signals, BWs 5%	4.6	5.4	5.9	6.5	7.3	8.6
4 BPSK signals, BWs 2%	2.3	2.6	3.1	4.0	5.2	6.6

Table 3: BW estimation accuracy of LAD ACC+NT, case (a).

	Estimated average BWs					
	SNR [dB]					
	0	5	10	15	20	25
2 BPSK signals, BWs 5%	5.0	5.5	5.9	6.6	7.8	10.0
2 BPSK signals, BWs 7%	6.3	7.1	7.7	8.2	9.1	10.5
2 BPSK signals, BWs 10%	8.7	10.2	11.1	11.7	12.4	13.6

Table 4: BW estimation accuracy of LAD ACC+NT, case (b).

	Estimated average BWs					
	SNR [dB]					
	0	5	10	15	20	25
2 BPSK signals, BWs 5%	5.0	5.6	6.0	6.7	7.8	9.4
2 BPSK signals, BWs 7%	6.1	7.1	7.7	8.3	9.1	10.3
2 BPSK signals, BWs 10%	1.9	10.0	11.1	11.8	12.4	13.3

BW estimation results are shown in Tables 2– 4. Monte Carlo studies include 10^5 iterations. The BW estimation results are presented only for the LAD ACC and LAD ACC+NT methods because the BW estimation performance of the original LAD method is almost the same [14]. Table 2 shows the estimated BWs for the LAD ACC method. Especially at low SNR, the LAD ACC method achieves relatively good BW estimates. For example, when there are two simultaneous BPSK signals with BWs of 10% and 10 dB SNR, estimated BWs are, on average, 10.9%. The estimated BWs when the combinations LAD ACC+NT case (a) and LAD ACC+NT case (b) were used are presented in Tables 3 and 4, respectively. The results are somewhat similar as in the previous case. At high SNR values, the rising sidelobes widens the estimated BW.

V. CONCLUSIONS

The performance of the two threshold based narrowband signal detection method called the LAD method was studied as a cognitive radio perspective. The enhanced version of the LAD which uses adjacent cluster combining as well as a new simplified version of the LAD that applies normalized thresholds were proposed and studied. The computer simulations show that the proposed methods have a good performance, and the use of enhanced version of the LAD method offers a remarkable advantage when estimating the number of narrowband signals present.

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