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A Comparison of FFT and Polyphase Channelizers

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Abstract

In this report, an analysis of the signal detection capabilities of two different channelizing filter techniques was carried out. The filtering techniques used were the FFT channelizer and the Polyphase channelizer, with each of five different windows: the Boxcar, Bartlett, Hanning, Hamming, and Blackman windows. These were evaluated to determine their ability to detect a single signal, and to differentiate between two signals, both with and without noise. For testing purposes, simulated signal and noise data were used. This evaluation has lead to a better understanding of the strengths and weaknesses of the filtering techniques, and their relative performance in certain situations.

Résumé

Dans ce rapport, une analyse des capacités de détection pour deux techniques différentes de filtrage à découpage en canaux a été réalisée. Les techniques de filtrage utilisées sont le canaliseur à tranformée de Fourier rapide et le canaliseur polyphase, avec pour chaque technique les cinq fenêtres suivantes: Boxcar, Bartlett, Hanning, Hamming et Blackman. La capacité des techniques à détecter un signal unique ainsi qu'à différencier entre deux signaux différents, et tout ceci en présence ainsi qu'en l'absence de bruit, a été évaluée. Pour des fins d'expérimentation des données simulant signal et bruit furent utilisées. Cette évaluation a permis une meilleure compréhension des forces et faiblesses des techniques de filtrage, ainsi que leur performance respective dans des situation données.

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Executive summary

Over the last two decades, rapid technological advances have lead to a dramatic change in the way Communications Electronics Support Measures systems are being designed. This has brought about another change: the introduction of the wideband digital receiver. Advantages of this new technology are that a larger portion of the signal spectrum can be examined at one time, and a desired frequency band can be scanned more quickly. One drawback of the digital wideband receiver is that by covering such a large part of the spectrum, it generates a correspondingly large data output. This problem is commonly addressed by using a filterbank to separate the data into consecutive frequency channels covering the receiver pass band. This is called channelization.

This report examines the Fast Fourier Transform (FFT) and polyphase channelizers to determine which is the best approach for frequency channelization of the signal data. The FFT channelizer is a fast implementation of the Fourier transform and was developed in 1965 [1]. It has since become a cornerstone in modern digital signal processing. The polyphase channelizer, a more recent development [2], implements the frequency channels using standard FIR filters while taking advantage of the processing speed of the FFT. This gives the polyphase approach greater flexibility in terms of shaping the channel gain response (with respect to frequency) without unnecessarily sacrificing processing speed. The effects of five different window functions (used by both channelization methods) were also examined. These functions included the Boxcar, Bartlett, Hanning, Hamming, and Blackman windows.

Overall, the analysis highlighted important aspects of the FFT and polyphase channelizers. The FFT channelizer has the advantage that for each block of N data values processed (where N is also the number of channels), the required number of computations is proportional to $N \log N$. The primary disadvantage is that the channel filter response is far from ideal with as much as a -4 dB change in gain from the center to the edge of the channel and high sidelobes (as much as -14 dB). The reduction in gain away from the center of the channel will reduce the effective SNR of signals whose center frequency is not aligned with the center frequency of the channel or modulated signals whose bandwidth is not small relative to the channel width. The high side lobes significantly degrade the ability to detect (and demodulate) weak signals in the presence of strong adjacent signals. Window functions can be used to reduce the sidelobes to more acceptable levels and improve detection performance when strong signals are present. Of the windows tested, the Blackman and Hanning windows were the best in this respect. The use of windows, however, does lead to a 1-2 dB reduction in detection performance and reduces the frequency resolution.

The polyphase channelizer has the advantage that the channel filter can be adjusted to better approximate the ideal magnitude response. Window functions can also be used to improve the sidelobe response without any of the performance penalties associated with the FFT channelizer. Compared to the FFT channelizer, the result is as good or better

detection performance for signals in noise, and substantially better performance for the detection of weak signals in the presence of strong signals. The main disadvantage is that larger data block sizes are required, $N \times P$, so that the processing requirements are proportional to $P \times N \log N$, where N is the number of channels and $N \times P$ is the data block size.

Ultimately, the best choice is dependent on the application. In real-time applications where processing speed is critical, the FFT channelizer will often be the only choice. For applications requiring superior performance, the polyphase channelizer is the better choice, especially given the flexibility it allows in shaping the channel frequency response. The drawback is increased processing time and an increased observation window (i.e. more input samples required to produce each output sample). In the end, the choice between the FFT and polyphase channelizers comes down to speed versus performance.

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Sommaire

Durant les 20 dernières années, de rapides progrès technologiques ont conduit à des changements majeurs dans la facon dont sont conçus les systèmes de communication de mesures de soutien électronique. Ceci a débouché sur un autre changement: l'introduction du récepteur numérique à large bande. Les avantages de cette nouvelle technologie résident dans le fait qu'une plus grande portion du spectre du signal peut être examinée en une seule fois, et aussi que la bande de fréquence désirée peut être balayée plus rapidement. Du fait qu'il couvre une portion importante du spectre, le récepteur numérique à large bande présente l'inconvénient de produire une sortie de données également importante. Ce problème est habituellement résolu par l'utilisation d'un banc de filtres qui sépare les données dans des voies de fréquences consécutives tout en couvrant la bande passante du récepteur dans son intégralité. Ce procédé est appellé le découpage en canaux.

Ce rapport évalue le canaliseur à tranformée de Fourier rapide et le canaliseur polyphase afin de trouver la meilleure approche pour le découpage en canaux des données. Le canaliseur à transformée de Fourier rapide est une implémentation rapide de la transformée de Fourier et fut développé en 1965 [1]. Il est devenu depuis une pierre angulaire du traitement de signal numérique. Le canaliseur polyphase, qui est un développement plus récent [2], effectue le découpage en canaux de la fréquence en utilisant des filtres à réponse finie à une impulsion standards, tout en prenant avantage de la rapidité d'exécution de la transformée de Fourier rapide. Ceci donne à cette dernière approche une plus grande flexibilité en terme de mise en forme de la réponse du gain des canaux (en fonction de la fréquence) sans nécessairement sacrifier la vitesse de traitement. L'effet de l'utilisation de cinq fonctions fenêtres différentes (utilisée pour les deux méthodes de découpage en canaux) fut aussi étudié. Ces fonctions fenêtres sont les fenêtres Boxcar, de Bartlett, de Hamming, de Hanning et de Blackman.

Dans l'ensemble, l'analyse mit en évidence des propriétés importantes des canaliseurs à transformée de Fourier rapide et polyphase. Le canaliseur à transformée de Fourier rapide présente l'avantage que pour chaque bloc de N données traitées (où N est aussi le nombre de canaux), le nombre requis de calculs est proportionnel à $N \log N$. L'inconvénient principal est que la réponse du filtre de chaque canal est loin d'être idéale. En effet une variation dans le gain, pouvant aller jusqu'à -4 dB, entre le centre et l'arête du canal combinée à des lobes secondaires pouvant monter jusqu'à 14 dB sous le lobe principal sont observés pour ce type de filtre. Cette réduction dans le gain dès que l'on s'éloigne du centre du canal réduira le rapport signal sur bruit effectif pour les signaux dont la fréquence centrale n'est pas alignée sur la fréquence centrale du canal, ainsi que pour les signaux modulés pour lesquels la bande passante n'est pas étroite relativement à la largeur du canal. Les hauts lobes secondaires dégradent d'une facon significative la capacité de détecter (et de démoduler) de faibles signaux en présence de signaux adjacents forts. Les fonctions fenêtres peuvent être utilisées pour réduire la hauteur des lobes secondaires à un niveau plus acceptable et ainsi améliorer la performance de détection du canaliseur en présence de forts signaux. Parmi toutes les

fenêtres évaluées, les fenêtres de Blackman et de Hanning furent les meilleures à ce point de vue. En contre partie l'utilisation de fonctions fenêtres se fait au détriment de la performance de détection (réduction de 1 à 2 dB) et de la résolution en fréquence.

Le canaliseur polyphase présente l'avantage d'avoir des filtres qui peuvent être ajustés afin de mieux approximer la réponse en grandeur idéale. Les fonctions fenêtres peuvent aussi être utilisée pour améliorer la réponse des lobes secondaires sans toutefois être pénalisé dans la performance de détection comme c'est le cas pour le canaliseur à transformée de Fourier rapide. Comparé au canaliseur à transformée de Fourier rapide le canaliseur polyphase donne d'aussi bons ou de meilleurs résultats en ce qui concerne la performance de détection des signaux en présence de bruit. Pour la performance de détection de faibles signaux en présence de forts signaux il donne de bien meilleurs résultats. Le principal inconvénient est que des blocs de données plus importants sont requis, $N \times P$, si bien que les exigences pour le traitement sont proportionnelles à $P \times N \log N$, où N représente le nombre de canaux et $N \times P$ la taille du bloc de données.

Finallement, le meilleur choix dépend de l'utilisation. Pour une utilisation en temps réel, où la vitesse de traitement est primordiale, le canaliseur à transformée de Fourier rapide sera souvent la seule option. Lorsque des performances supérieures sont exigées, le canaliseur polyphase est le meilleur choix, compte tenu notament de la flexibilité qu'il permet dans la mise en forme de la réponse de fréquence des canaux. Le désavantage est que son utilisation nécessite un temps de traitement et une fenêtre d'observation plus importants (par example davantage d'échantillons d'entrée seront requis pour produire chaque échantillon de sortie). Finalement choisir entre le canaliseur à transformée de Fourier rapide et le canaliseur polyphase revient à choisir entre vitesse et performance.

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1. Introduction

The rapid technological advances that have occurred over the last two decades have lead to a dramatic change in the way that Communications Electronics Support Measures systems are being designed. Intercept system designs employing narrowband fast scanning analog receivers and analog processors have already seen the replacement of most of analog subsystems (except the receiver RF section) by more reliable and accurate digital subsystems. The proliferation of advanced low probability of intercept transmitters, such as frequency hoppers, on the modern battlefield has motivated yet another change: the introduction of the wideband digital receiver concept.

The obvious advantage of a wideband receiver is that large portions of the signal spectrum can be examined simultaneously (compared to a narrowband system which must scan) so that new signals can be detected with a 100% probability (i.e. won't be missed due to the scan period the would have been required by a narrowband scanning receiver). Alternatively, when used in a scanning mode to cover a larger frequency range, the wideband receiver can achieve a much shorter search time than a narrowband system.

One drawback of the digital wideband receiver is that by covering a much larger part of the spectrum, it generates a correspondingly greater data output than a digital narrowband system. The most common approach taken to address this problem is to use a filterbank to separate the data into consecutive frequency channels covering the receiver pass band. The output of one frequency channel would then be equivalent to the output of a narrowband receiver. Given that most communications signals are narrowband[1], then only the filter channels where signals are detected need be retained, while the rest can be ignored. As the number of signal channels is typically only a few percent of the total number of channels, this approach considerably reduces the downstream processing requirements.

A natural question that arises is what is the best approach for frequency channelization of the data. For realtime applications, approaches which are computationally efficient are a necessity. Hence, in this report, the Fast Fourier Transform (FFT) channelizer and the polyphase channelizer were chosen for study and comparison. The FFT channelizer is a fast implementation of the Fourier transform and was developed in 1965 [1]. It has since become a cornerstone in modern digital signal processing. The polyphase channelizer, a more recent development [2], implements the frequency channels using standard FIR filters while taking advantage of the processing speed of the FFT. This gives the polyphase approach greater flexibility in terms of shaping the channel gain response (with respect to frequency) without unnecessarily sacrificing processing speed.

The main goal of the analysis reported here was to assess the performance of each method for detecting a signal given that recovering the message content of the signal

[1]Except PCS signals, which are wideband and likely to be processed using specialized wideband systems. This report only considers the more general application.

(e.g. demodulation) is the ultimate goal. This ultimate goal needs to be considered when detection is discussed. For example, in [3] methods are discussed which are capable of detecting the presence of short duration signals at very low signal-to-noise power ratios (SNR) using signal averaging techniques. However, since these averaging techniques destroy the message content of the signal, even though the signal is detected it may not be possible to extract this message content (i.e. demodulate it) because the SNR is too low. For this reason, signal averaging techniques are not considered here.

In the analysis, two conditions which commonly occur in the real world were evaluated: a single signal in the presence of noise, and a weak signal in the presence of noise and a much stronger cochannel signal. Additionally, as part of this analysis, the effects of using five different types of window functions (used by both channelization methods) were also examined. These functions included the Boxcar, Bartlett, Hanning, Hamming, and Blackman windows.

In this report, background information is given on the channelizing methods and the five windows, as well on the methods and results of the experiments used to compare them. The FFT and polyphase channelizers, and the five windows, are described in Section 2. The experiments comparing the two channelizers, and the results of these experiments, are discussed in Section 3. Finally, some concluding remarks are provided in Section 4.

2. Channelization

In this section the implementation details of the FFT and polyphase channelizers are discussed.

2.1 FFT Channelizer

For realtime processing, the FFT channelizer is a simple and attractive choice. Mathematically, the channelized output values can be represented by

$$y_k(m) = \sum_{n=0}^{N-1} w(n)x(n+mN)e^{-j2\pi f_s kn/N} \quad \text{for} \quad m = 0, 1, 2, ... \tag{1}$$

where N represents the number of samples in each FFT block, $w(n)$ represents the window function (discussed shortly), $x(n)$ represents the receiver output data stream, f_s represents the complex sampling rate of $x(n)$, and $k = 0, 1, ..., N-1$ represents the frequency channel number. Since the channel bandwidth f_c is given by f_s/N, the FFT blocksize N is given by

$$N = \frac{f_s}{f_c} \tag{2}$$

Implemented directly, (1) requires on the order of N^2 operations to compute the channel values $y_0, ..., y_{N-1}$ for a single block of N data points, and is called the Discrete Fourier Transform. However in [1], it is shown that for $N = 2^i$, where i is a positive integer, and taking advantage of intermediate results, the number of computations can be reduced to on the order of $N \log N$ operations (hence the name Fast Fourier Transform).

Inspecting (1) shows that since only a single value is produced in each frequency channel for each block of N input data values, the sampling rate for each frequency channel is reduced to F_s/N. This is also based on consecutive data blocks of N data points being used for the FFT. If overlapping blocks are used instead, the channel sampling rate will be raised, becoming F_s/N_s, where N_s is the block shift value and $N_s < N$. In this report, overlapping blocks are not considered.

Examples of the channel response for the FFT channelizer are shown in the following section.

2.1.1 FFT Windows

Windowing functions, or windows, are used to suppress undesirable sidelobe effects which occur when the Fourier transform is used on finite length data blocks.

One problem with the Fourier transform is sidelobe effects, which are a consequence of finite length data blocks being used. In the channelizing application, higher sidelobes translate to higher interference from signals appearing in channels that are close in frequency to a given channel. This can become a problem in dense signal environments where the goal is to demodulate a target signal in the presence of strong inband signals.

One method of suppressing sidelobes is to use a window function as represented by $w(n)$ in (1). Sidelobe suppression comes at the expense of frequency resolution (see [4]), which results in a channel bandwidth larger than f_s/N. Although this reduces selectivity and thereby increases the sensitivity to adjacent channel interference, the overall reduction in sensitivity to inband interference makes the use of windows a desirable compromise for many applications.

Five standard windows functions are considered in this report, and these window functions are: Boxcar, Bartlett, Hanning, Hamming, and Blackman. Their descriptions follow.

The first window, the Boxcar window, is given by

$$w(n) = 1.0, \qquad n = 0, 1, \ldots, N-1; \tag{3}$$

and is equivalent to the "no-window" condition. The window shape is shown in Figure 1a. An example of the channel gain response is shown in Figure 2a. The ideal channel response would have a gain of exactly one across the desired channel (i.e. an abscissa value of -0.5 to 0.5 in Figure 2a) and zero everywhere else. By comparison, the actual gain is not constant across the desired channel, nor is it zero everywhere else (there are significant sidelobes), leading to the interference problems already discussed.

The second window, the Bartlett window, uses a simple triangular taper given by

$$w(n) = \begin{cases} \frac{n}{N/2}, & \text{n = 0, 1,} \ldots, \frac{N}{2} \\ \\ w(N-n), & \text{n = } \frac{N}{2}, \ldots, \text{N-1} \end{cases} \tag{4}$$

and is shown in Figure 1b. An example of the channel response is shown in Figure 2b. The tapering leads to significantly lower sidelobes while widening the main lobe. This reduces the overall susceptibility to interference except for the adjacent channels.

The third window, the Hanning window, is more smoothly varying and is given by

$$w(n) = 0.5 + 0.5cos\left[\frac{2n}{N}\pi\right], \qquad n = 0, 1, \ldots, N-1, \tag{5}$$

and is shown in Figure 1c. An example of the channel response ($N = 2048$) is shown in Figure 2c. The sidelobe levels are even lower than the previous two windows, but the main lobe is again wider.

The fourth window, the Hamming window, is given by

$$w(n) = 0.54 - 0.46cos\left[\frac{2n}{N}\pi\right], \qquad n = 0, 1, \ldots, N-1, \tag{6}$$

and is shown in Figure 1d. This window is very similar to the Hanning window, with minor adjustments to increase sidelobe cancellation (also note that it does not taper to zero). An example of the channel response is shown in Figure 2d.

The fifth window, the Blackman window, is given by

$$w(n) = 0.42 - 0.5cos\left[\frac{2n}{N}\pi\right] + 0.08cos\left[\frac{4n}{N}\pi\right], \qquad n = 0, 1, \ldots, N-1, \tag{7}$$

and is shown in Figure 1e. An example of the channel response is shown in Figure 2e. This window yields the lowest sidelobe levels of the five windows, but also the widest main lobe.

An important observation here is that regardless of the window, the filter gain drops towards the edge of the channel. In the case of the Boxcar window, this drop is as much as 4 dB. This is not a desirable behavior since it reduces the ability to detect signals near the channel edges when the signal-to-noise is low, and can lead to distortion effects for modulated signals due to frequency to amplitude conversion.

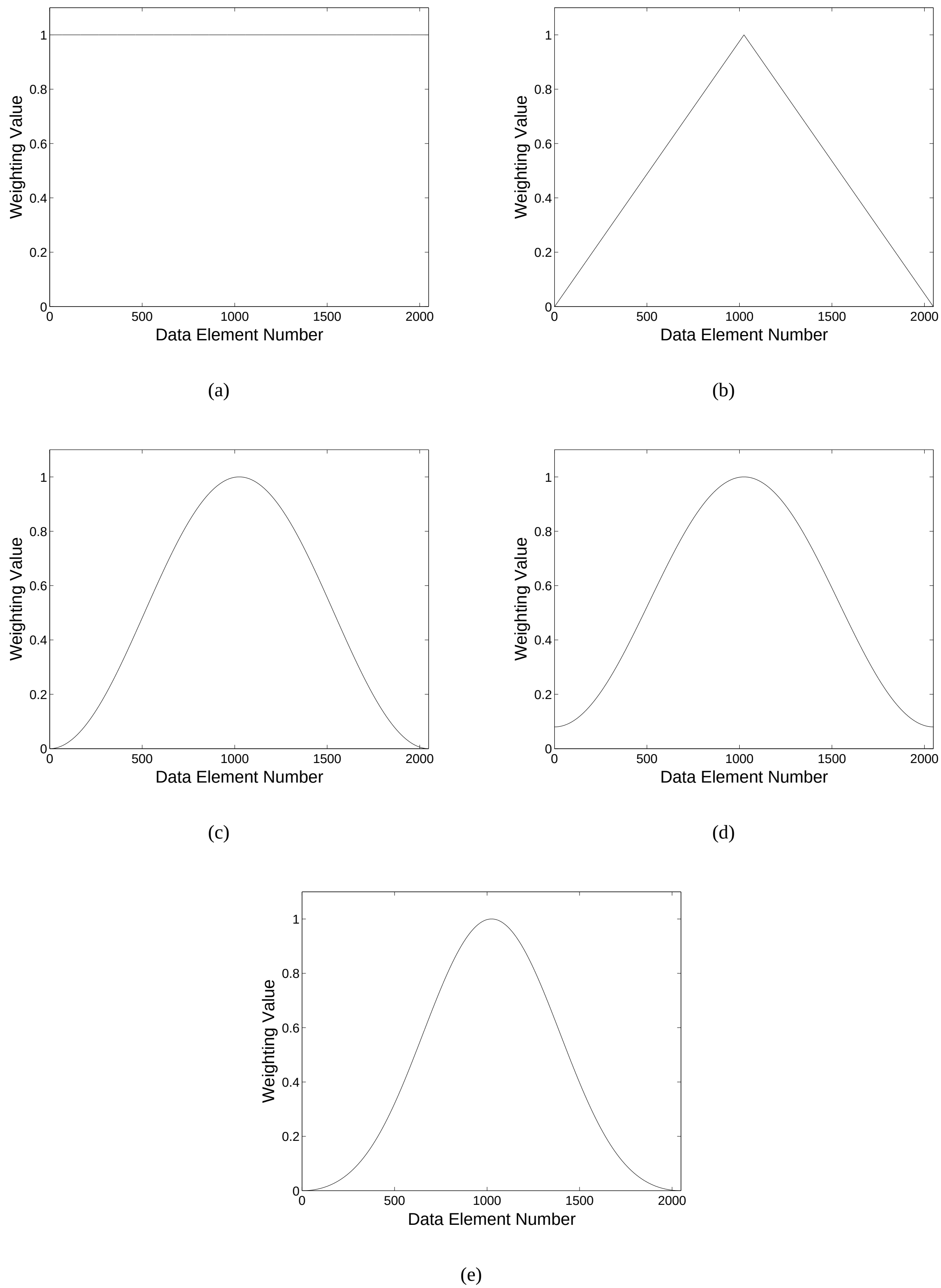


Figure 1: *Shapes of the following window functions (N = 2048): (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman*

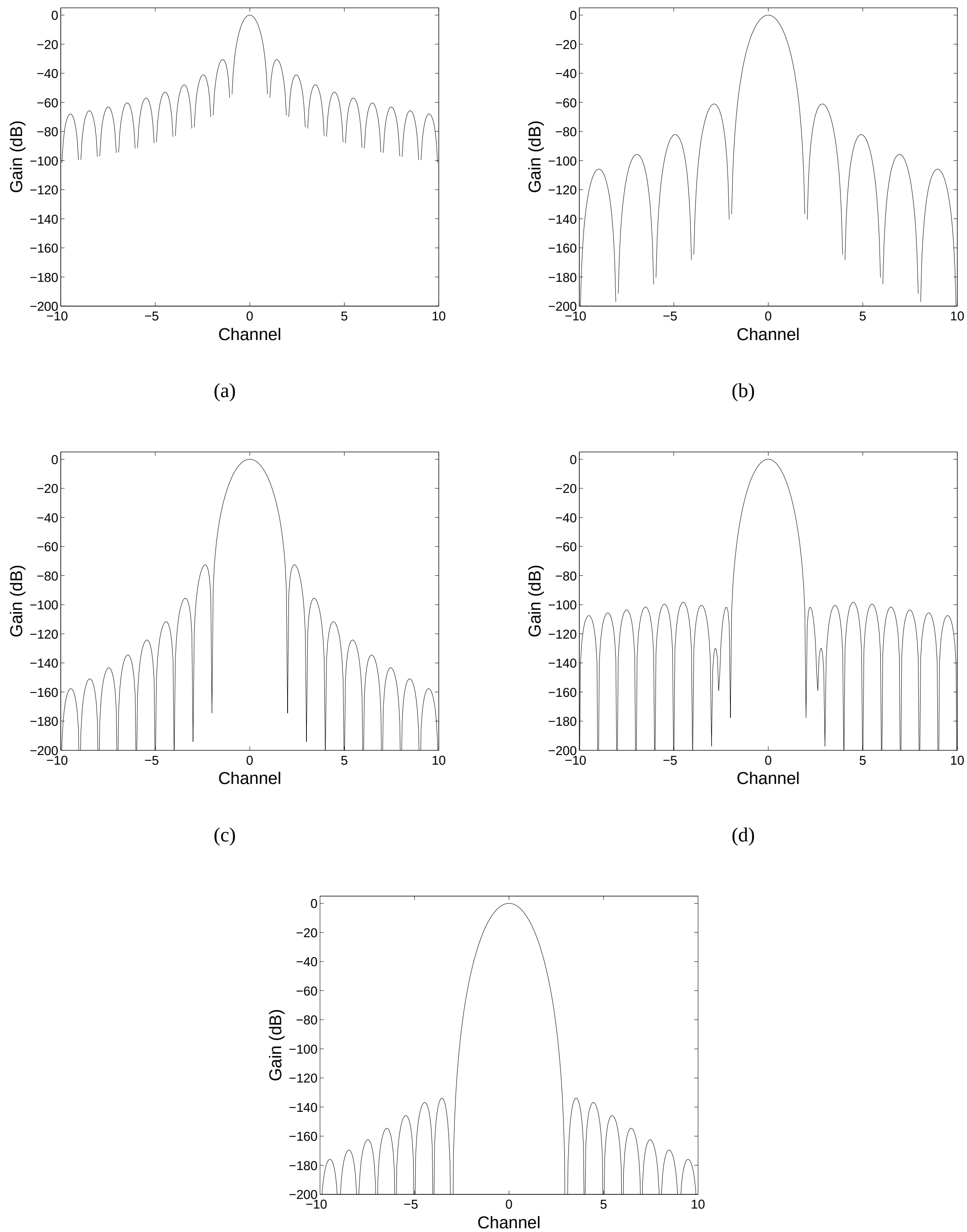


Figure 2: *Examples of the FFT channel gain response (with respect to frequency) for $N = 2048$ and using the following window functions: (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman. The response is shown for the desired channel (designated 0 in this case) and the 10 adjacent channels on either side.*

2.2 Polyphase Channelizer

One of the shortcomings of the FFT channelizer is that it has very little flexibility in terms of shaping the gain response of the frequency channels. This can lead to cochannel signal interference when there is very strong inband interference relative to the desired signal, as well as reduced detection sensitivity and distortion effects. An alternate approach, which overcomes these limitations, is based on using FIR filters. The FIR filter equation for a $N \times P$-tap filter is given by

$$y(m) = \sum_{n=0}^{NP-1} x(n+mN)h(n) \tag{8}$$

where $h(n)$ represents the filter coefficients which are chosen (along with the number of taps, P) to provide the desired channel gain response. As in the case of the FFT channelizer, the channel sampling rate will be $f_c = f_s/N$, since a block shift of N has been employed (in this case there is overlap since the data block size is NP). Like the FFT channelizer, other block shift values could be used, but, to be consistent, only a shift value of N is considered.

In theory, a filter could be designed for every channel which has the desired gain profile, center frequency, and channel bandwidth of f_s/N. However, this leads to an unnecessarily complicated arrangement which is also computationally intensive . A simpler approach is to use a single low-pass filter and then appropriately shift the data in frequency before passing the data through the filter. Appropriately modifying the filter equation gives

$$y_k(m) = \sum_{n=0}^{NP-1} x(n+mN)e^{-j2\pi kn/N}h(n). \tag{9}$$

Although the ability to individually tailor the gain profile of each channel is lost, it is more desirable for the channelizing application that the profiles for each channel be identical.

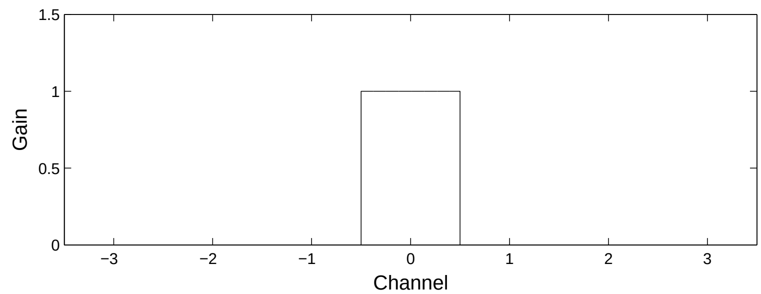
An extremely useful feature of this filter approach is that if the filter equation is written out in the following manner

$$\begin{array}{ccccc} & h(0)x(t) & + \;\ldots\; + & h(N-1)x(t-N+1)e^{-j2\pi f_s k(N-1)/N} \\ + & h(N)x(t-N) & + \;\ldots\; + & h(2N-1)x(t-2N+1)e^{-j2\pi f_s k(N-1)/N} \\ & \vdots & & \vdots \\ + & h(NP-N)x(t-NP+N) & + \;\ldots\; + & h(NP-1)x(t-NP+1)e^{-j2\pi f_s k(N-1)/N} \end{array} \tag{10}$$

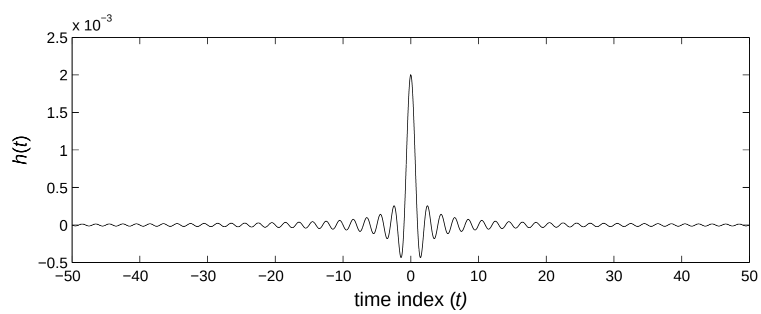
then it is evident that each row has the form of a Fourier transform. Hence a more efficient way to compute the channel values $y_k(t)$ is to premultiply the data by the filter coefficients and then arrange the data in the same manner as above except *without* summing the data. If N is chosen as a power of 2 (i.e. $N = 2^i$ where i is a positive integer), the FFT channelizer is then performed on each row in succession and the results from like FFT frequency bins are summed together to give the N channel values $y_0(t), ..., Y_{N-1}(t)$. Using the FFT, the number of computations is reduced from an order of N^2P^2 operations to $NP \log N$ operations.

The filter coefficients can then be chosen using a standard FIR filter design package to give the desired frequency profile and bandwidth. For this report, the selection procedure is discussed in the following section along with the corresponding filter response.

2.2.1 Polyphase Filter Coefficients



(a)



(b)

Figure 3: *Ideal channel filter response showing the (a) gain spectrum, and (b) the impulse response.*

The ideal channel filter response is shown in Figure 3a. The ideal impulse response of this filter is given by taking the inverse Fourier transform to get

$$\begin{aligned} h(t) &= \int_{-f_c/2f_s}^{f_c/2f_s} e^{j2\pi fn} df \\ &= \frac{f_c}{f_s}\text{sinc}(\frac{f_c}{f_s}t) \end{aligned} \tag{11}$$

where $-\infty < t < \infty$. The impulse response for $-50 < t < 50$ is shown in

Figure 3b. Obviously, since this filter has an infinitely long impulse response, it is not useful for practical applications.

For a finite data block of NP discretely sampled values, the ideal filter response can be approximated by quantizing in time and truncating the impulse response. Hence, centering the truncation around $t = 0$ for the best result and given that NP is even-valued (since $N = 2^i$), then for the discrete approximation, the time index is restricted to

$$t = -NP/2 + 0.5,\ -NP/2 + 1.5, ..., -0.5, 0.5, ..., NP/2 - 1.5,\ NP/2 - 0.5 \tag{12}$$

This yields the discrete impulse response approximation given by

$$h(n) = \frac{f_c}{f_s}\ \mathrm{sinc}(\frac{f_c}{f_s}(n - NP/2 + 0.5)) \tag{13}$$

where $n = 0, ..., NP - 1$. Examples of the gain response of this filter for different values of P are shown in Figures 4a - 7a.

An undesirable feature of the filter coefficients defined in (13) is the ripples in the pass band (most visible in Figure 5a) and the sidelobes in the stop band. Much like the FFT channelizer, these undesirable effects can be reduced using windows. Taking advantage of the these window functions, the filter coefficients can be redefined as

$$h(n) = \frac{w(n)}{N}\ \mathrm{sinc}((n - NP/2 + 0.5)/N) \tag{14}$$

where $w(n)$ represents the window function and $f_c/f_s = 1/N$ was used. The results of using the same windows described in Section 2.1.1 on the gain response of the polyphase filter are illustrated in Figures 4 - 7. The general effect of the windows is similar to before (when used with the FFT channelizer), with a slight widening of the filter passband and a dramatic reduction in the sidelobes. The comparative advantages of the various windows is also the same as before.

Overall, the polyphase channelizer yields a more desirable channel response than the FFT channelizer with a flatter passband, greater stopband suppression, and a more rapid transition between the passband and stopband. The disadvantage is that more data is required to compute the channel values, resulting in a factor of P more computations, and a larger minimum observation time for a given frequency resolution.

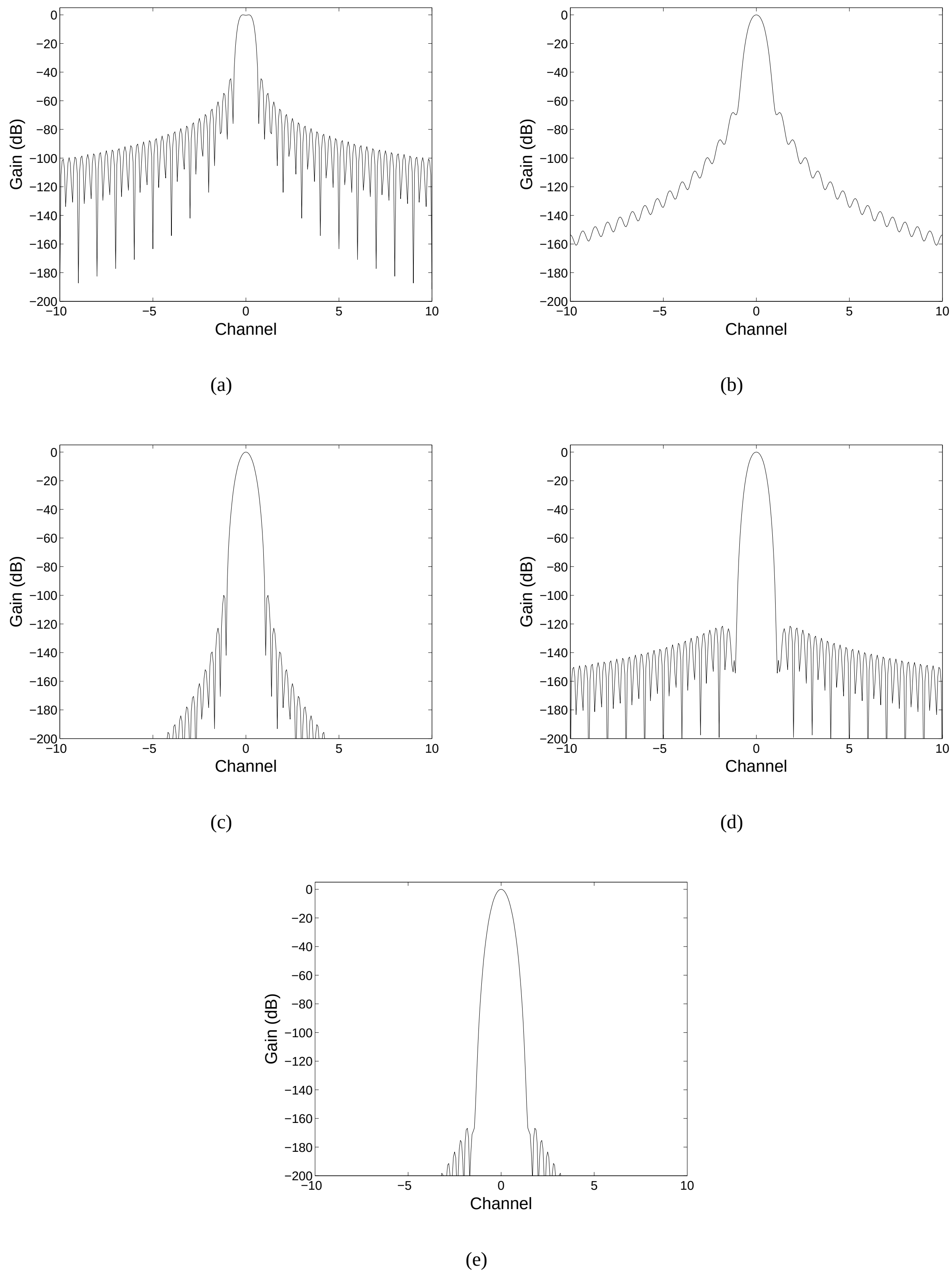


Figure 4: *Examples of the polyphase channel gain response (with respect to frequency) for* $(N, P) = (2048, 3)$ *and using the following window functions: (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman. The response is shown for the desired channel (designated 0 in this case) and the 10 adjacent channels on either side.*

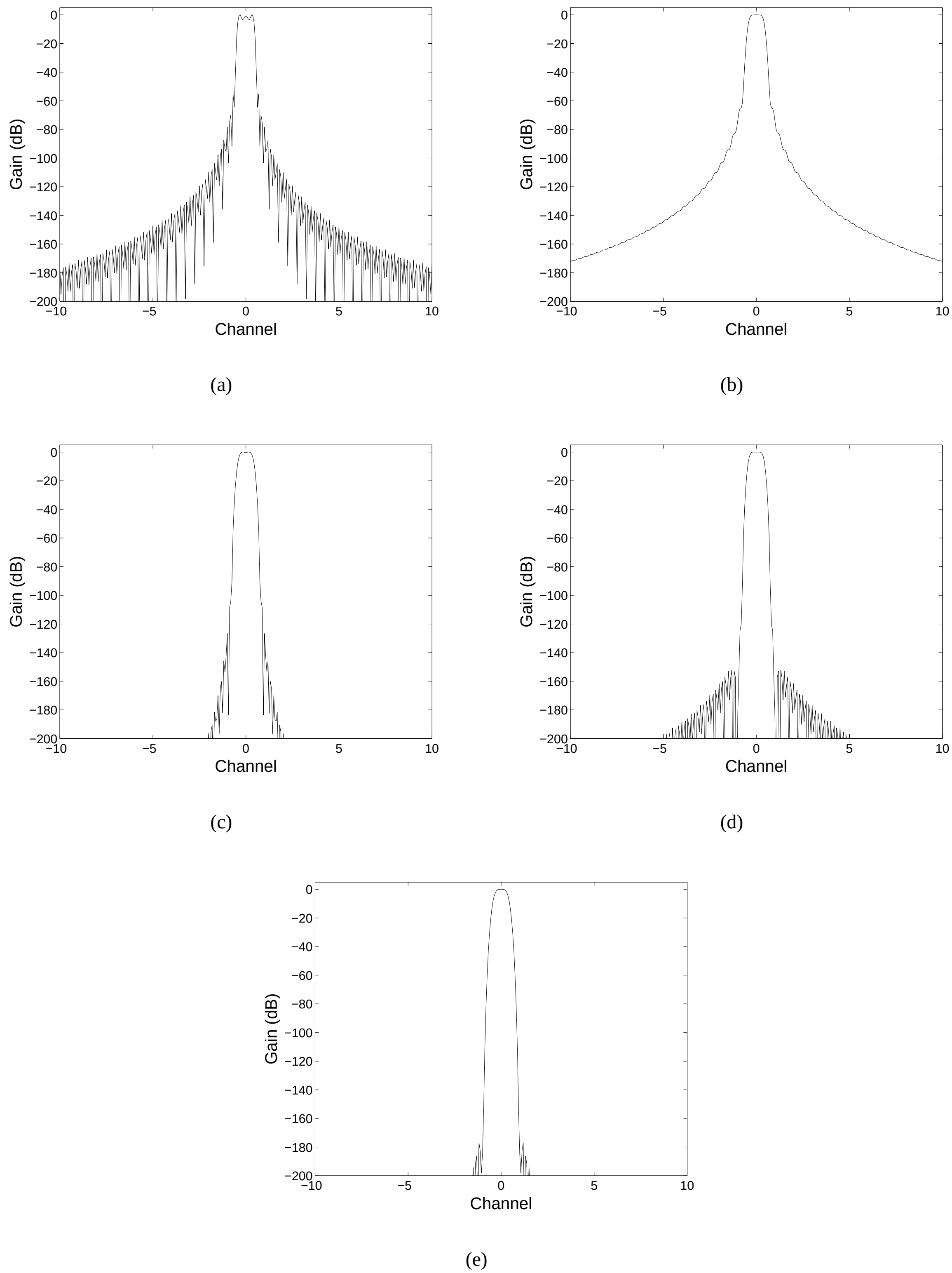


Figure 5: *Examples of the polyphase channel gain response (with respect to frequency) for* $(N, P) = (2048, 6)$ *and using the following window functions: (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman. The response is shown for the desired channel (designated 0 in this case) and the 10 adjacent channels on either side.*

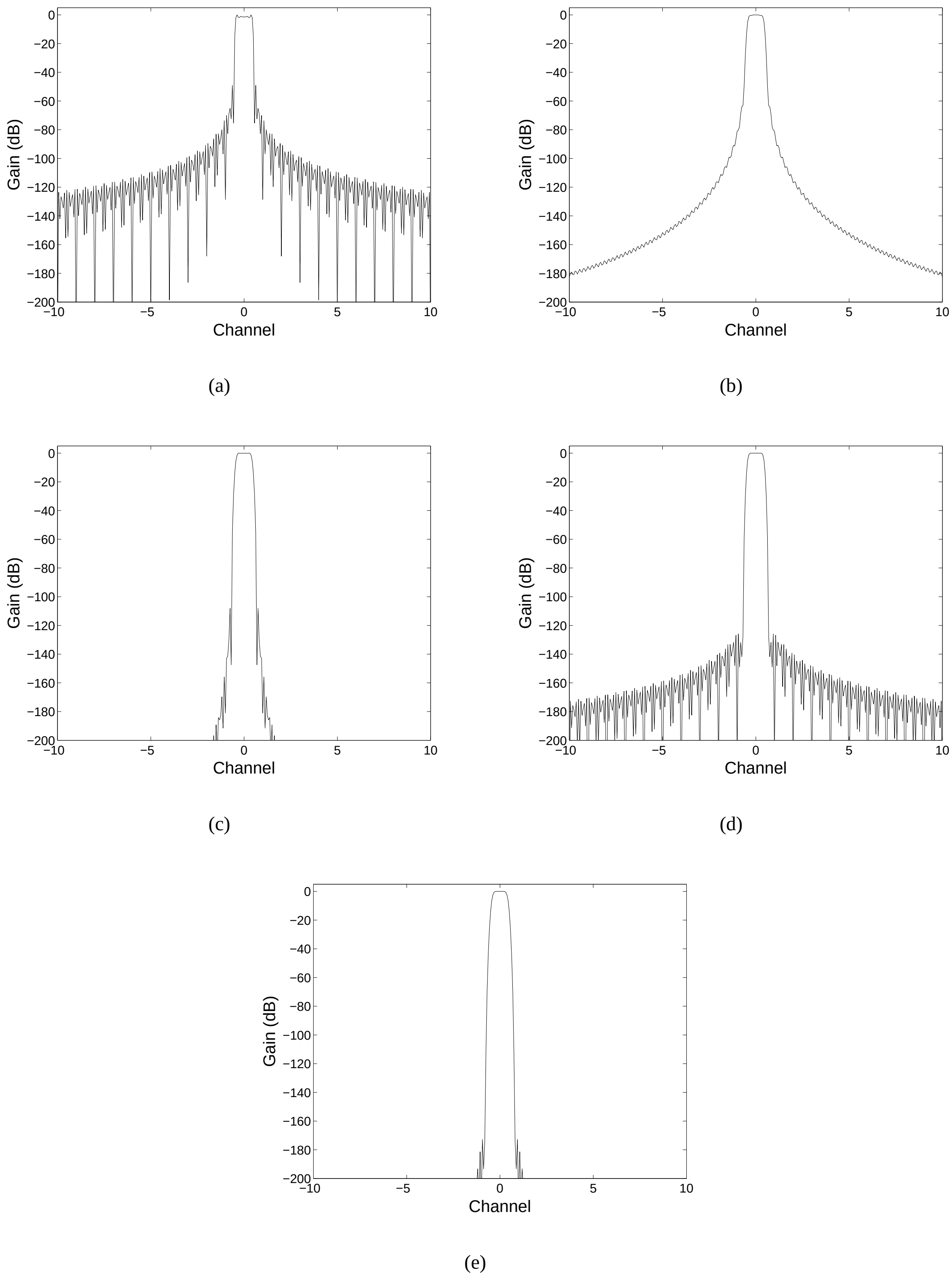


Figure 6: *Examples of the polyphase channel gain response (with respect to frequency) for* $(N, P) = (2048, 9)$ *and using the following window functions: (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman. The response is shown for the desired channel (designated 0 in this case) and the 10 adjacent channels on either side.*

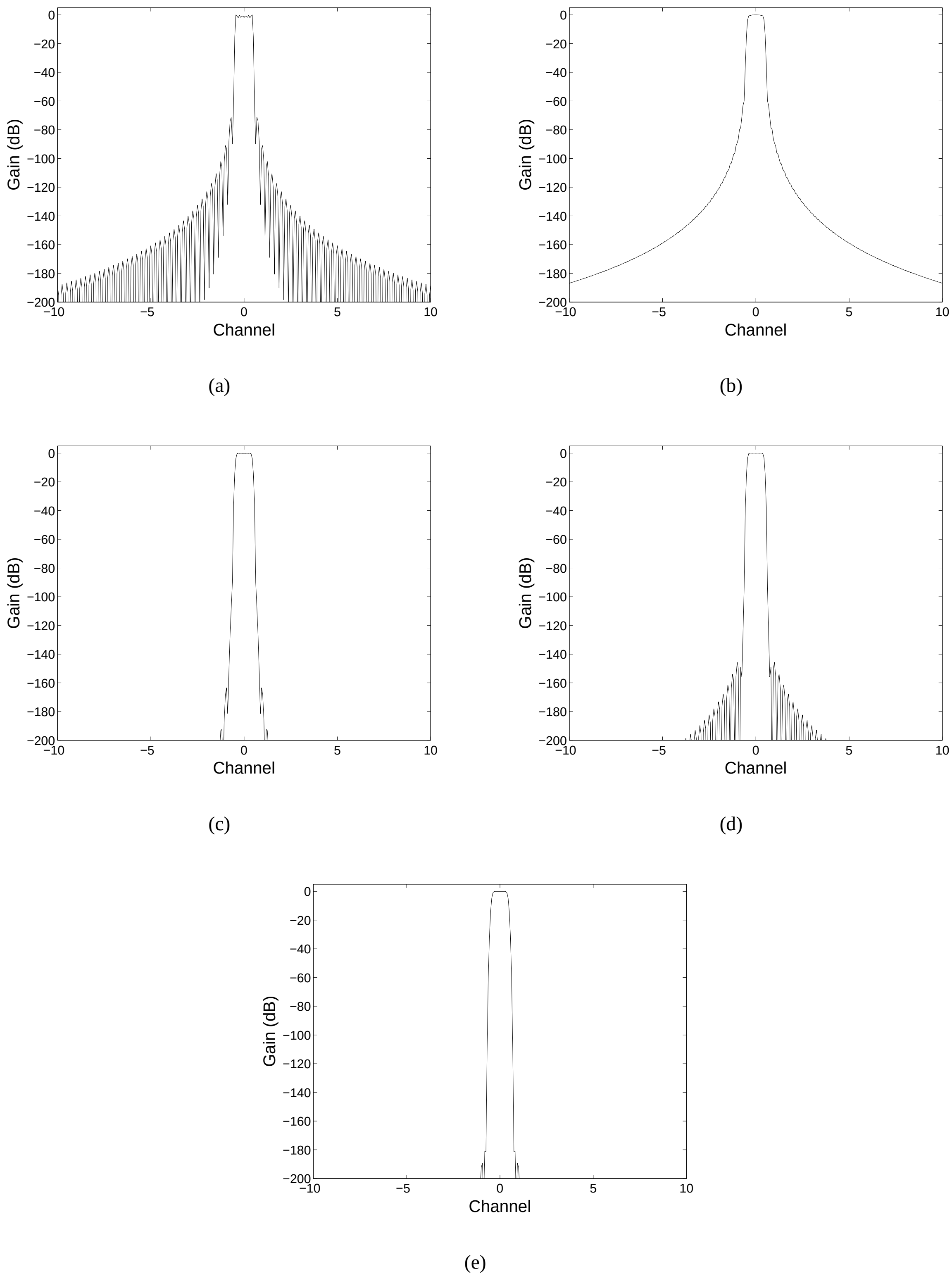


Figure 7: *Examples of the polyphase channel gain response (with respect to frequency) for $(N, P) = (2048, 12)$ and using the following window functions: (a) Boxcar, (b) Bartlett, (c) Hanning, (d) Hamming, and (e) Blackman. The response is shown for the desired channel (designated 0 in this case) and the 10 adjacent channels on either side.*

3. Comparing the FFT and Polyphase Channelizers

A number of conclusions could be drawn from the FFT and polyphase channel filter response, such as, for example, the polyphase approach has lower sidelobes so that cochannel interference would be expected to be less of a problem. Also, the ability to resolve signals close in frequency should be better.

To test whether these conclusions are valid, and to identify any other hidden problems, a number of Monte Carlo simulation experiments were run to test the FFT and polyphase channelizing approaches. The experiments and their results are described in the following sections.

3.1 Single Signal without Noise

In the first experiment, the processing results of the two channelizers were compared using data containing a single signal and *no* noise. Each of five different windows were also used in conjunction with the two channelizers. The objective was to comparatively assess behaviour in terms of leakage of the signal into channels where the signal is not supposed to appear (based on its frequency).

The input data for this experiment was a CW signal with a normalized frequency of $f = 0.1001$ and was defined as

$$x(n) = e^{j2\pi n0.1001} \qquad \text{for } \; n = 0, 1, 2, ..., NP - 1 \tag{15}$$

where N is the FFT blocksize and NP is the polyphase blocksize.

Using values of $N = 2048$ and $P = 12$, the corresponding values of $y(m)$ for $m = 0, 1, ..., N - 1$ were computed using both the FFT channelizer and the polyphase channelizer. Note that for the FFT, only the first N data points were used in the computation. The comparative results for all five windows are shown in Figures 8-12.

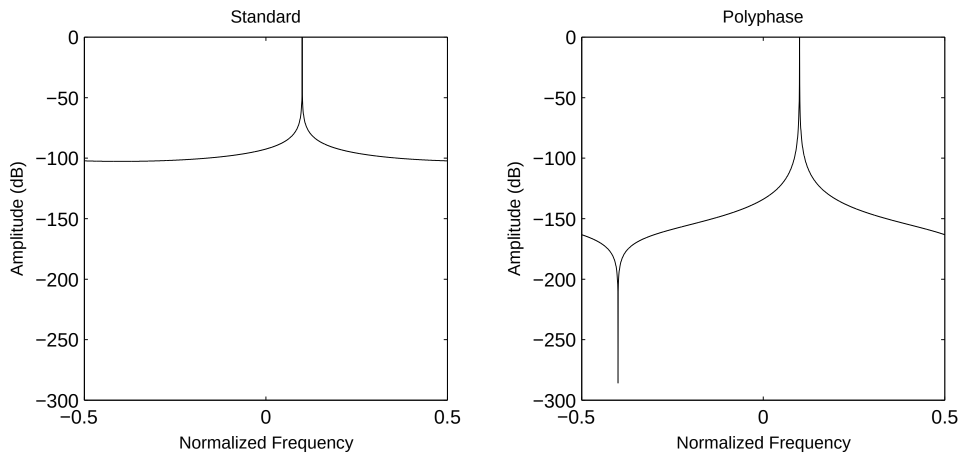


Figure 8: *Channelization results using the Boxcar window*

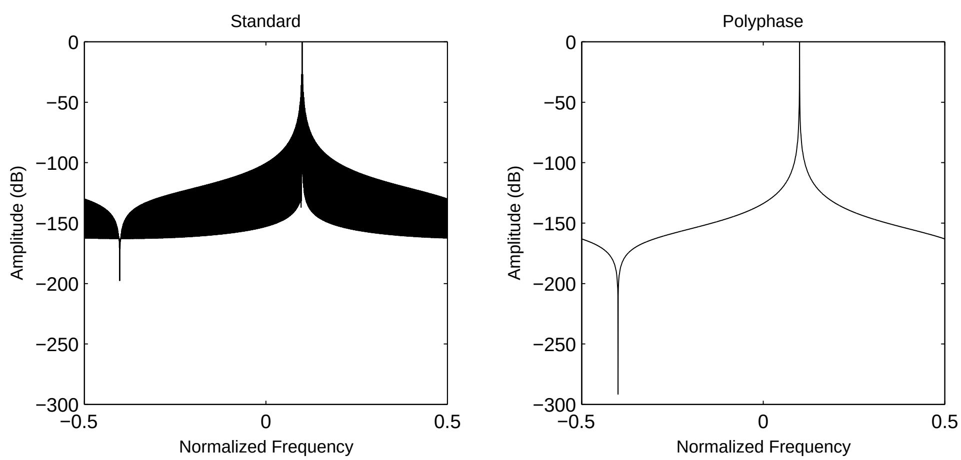


Figure 9: *Channelization results using the Bartlett window*

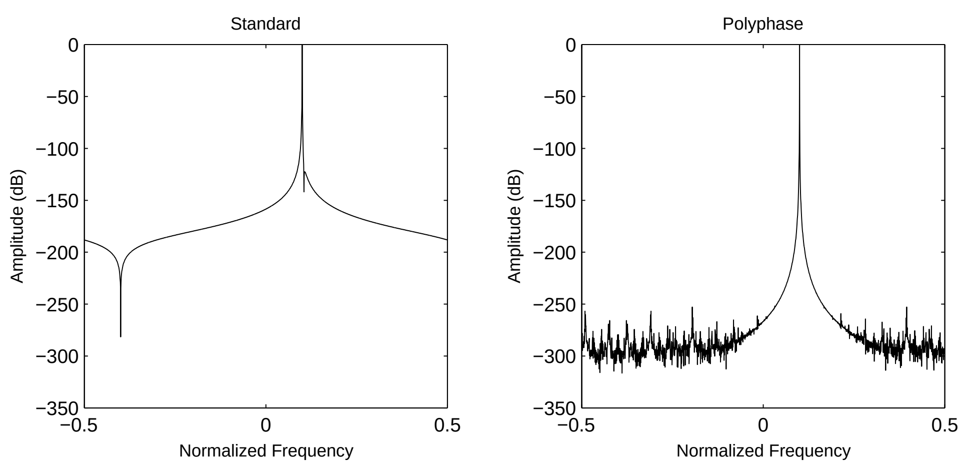


Figure 10: *Channelization results using the Hanning window*

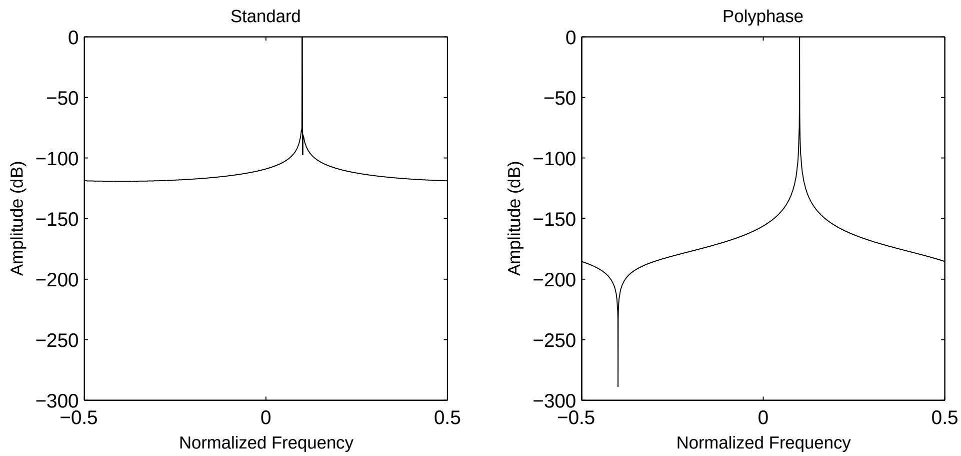


Figure 11: *Channelization results using the Hamming window*

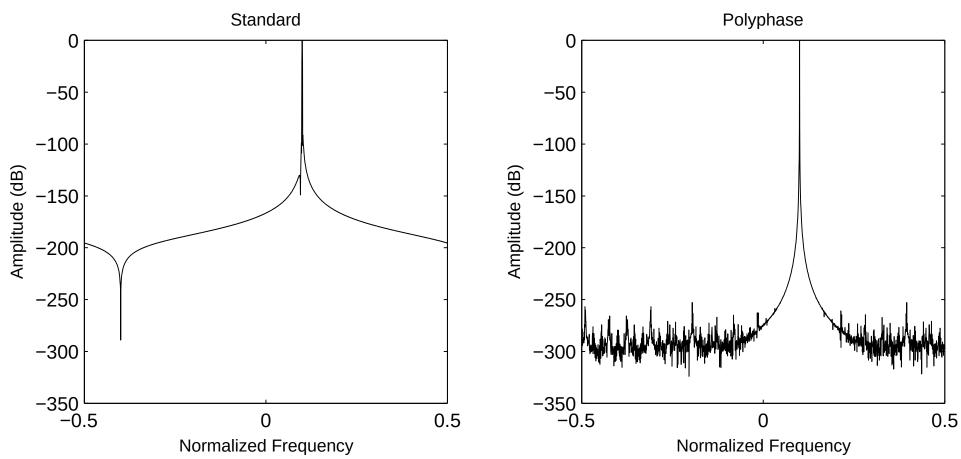


Figure 12: *Channelization results using the Blackman window*

Overall, the results show that the signal is easily detected in all cases, but that “leakage” of the signal into adjacent channels does occur, which could potentially interfere with the detection of weak signals. This leakage is reduced by using window functions, with the Blackman window yielding the lowest levels of the windows tested. The polyphase channelizer also exhibited substantially lower leakage than the FFT channelizer (up to 100 dB better for the Blackman window). In fact, for both the Hanning and Blackman windows, signal leakage is so low for the polyphase channelizer that the displayed spectrum exhibits the effects of finite-precision arithmetic (the noise-like peaks at -300 dB).

The leakage effects correspond to the filter sidelobes discussed in Section 2. In fact, the leakage levels are completely consistent with the sidelobe levels shown in Figures 2 and 7.

It is worth noting that for existing applications, 150 dB sidelobe suppression is more than sufficient for most applications, so that the performance of the FFT channelizer with the Hanning or Blackman windows appears to be acceptable, as does the performance of the polyphase channelizer with the Bartlett, Hanning, Hamming, or Blackman windows.

3.2 Single Signal with Noise

In the second experiment, the processing results of the two channelizers were compared using data containing a single signal with the noise level adjusted so that the signal could only be detected 320 times out of 400 trials (an 80% probability of detection). The purpose of this experiment was to comparatively assess detection performance in a high noise environment.

The input data for this experiment consisted of a single CW signal plus noise, and was defined as

$$x(n) = e^{j(2\pi nf+\theta_k)} + \sigma\eta_k(n) \qquad \text{for } \ n = 0, 1, 2, ..., NP-1 \tag{16}$$

where k is the trial number, $\sigma\eta_k(n)$ is zero-mean random white Gaussian noise with a variance of σ^2, θ_k is a uniform random variable distributed between 0 and 2π, N is the FFT blocksize, and NP is the polyphase blocksize.

Using both the FFT and polyphase channelizers to compute the corresponding values of $y(m)$ for $m = 0, 1, ..., N-1$ for each trial, a detection was considered to occur when $|y(k)| > |y(m)|$ for all values of $m \neq k$, and where k was the channel where the signal was expected to appear. If the signal was successfully detected more than 80% of the time, the value of σ was reduced and the trials were repeated. Likewise, if the signal was successfully detected less than 80% of the time, the value of σ was increased and the trials were repeated. In that way, σ was adjusted until the desired success rate was achieved.

This experiment was carried out using only the Hanning window, but doubling the number of channels according to $N = 16, 32, 64, 128, ..., 16384$. The parameter $P = 12$ was fixed for the polyphase channelizer. The signal frequency was also selected according to

$$f = \frac{\lfloor 0.1001N \rfloor}{N} \tag{17}$$

where $\lfloor a \rfloor$ represents the nearest integer equal to or less than a. The purpose of this choice was to force the signal frequency to line up with the center of the corresponding frequency channel, so that the filter roll-off effects (discussed in Section 2.1.1) would not affect the results.

The results are shown in Figure 13. The noise level was computed according to

$$\textit{Noise Level} = 20 \log \sigma. \tag{18}$$

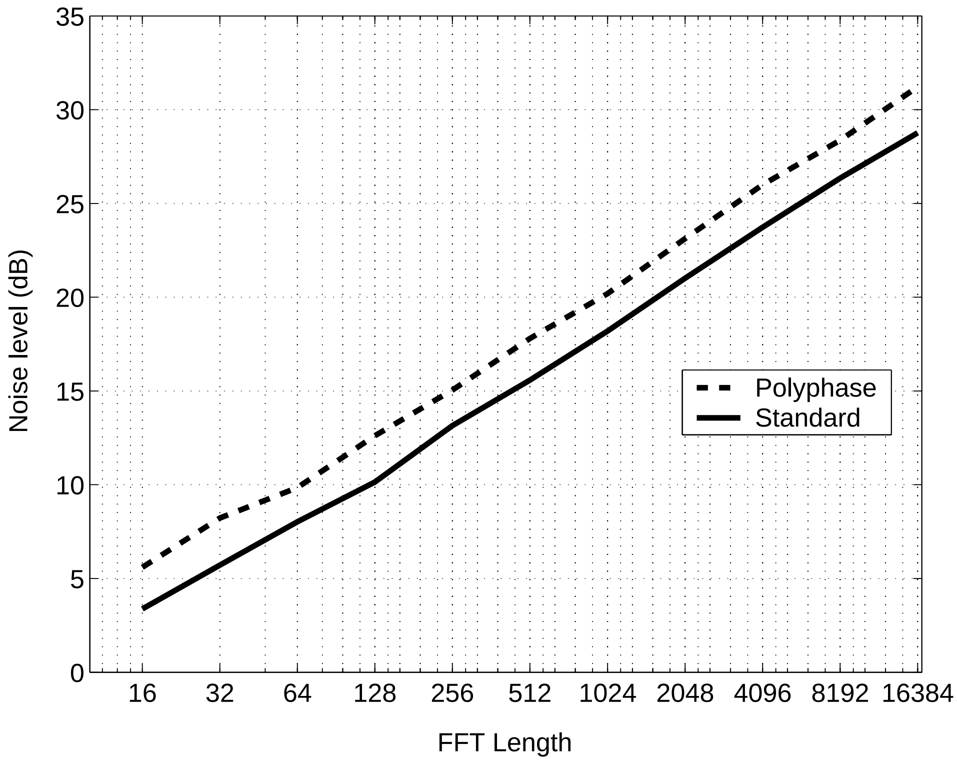


Figure 13: *Variation of the noise level yielding an 80% detection success rate as a function of the number of channels N*

(Note that since the signal had unity amplitude, the corresponding signal-to-noise ratio was $-20 \log \sigma$). Examining Figure 13, performance improves as N increases, so that the noise level has to be increased as a function of $10 \log N$ to maintain an 80% probability of detection, and the polyphase channelizer has a 2 dB advantage on the FFT channelizer.

The reason for this apparent improvement is due to the effect of windowing. For the FFT channelizer, windowing reduces the contribution of the data values near the start and end of each data block. The effect of this is different for the signal and the noise. For example, in the frequency channel corresponding to f, the signal adds coherently and the signal output power will be given by

$$\left(\sum_{n=0}^{N-1} w(n) \right)^2 \tag{19}$$

(given a signal with unity amplitude) while the noise adds noncoherently so that the noise output power will be given by

$$\sigma^2 \sum_{n=0}^{N-1} w(n)^2. \tag{20}$$

The output signal-to-noise power ratio will therefore be given by

$$\mathit{SNR} = 10\log\left(\left[\sum_{n=0}^{N-1} w(n)\right]^2\right) - 10\log\left(\sigma^2 \sum_{n=0}^{N-1} w(n)^2\right). \tag{21}$$

Comparing the change in the signal-to-noise power ratio with the Boxcar window ($w(n) = 1$) to any other window, the effective change in the signal-to-noise ratio due to windowing is given by

$$\Delta\mathit{SNR} = 10\log\left(\left[\sum_{n=0}^{N-1} w(n)\right]^2\right) - 10\log\left(N \sum_{n=0}^{N-1} w(n)^2\right). \tag{22}$$

For the Hanning window with $N = 2048$, $\Delta\mathit{SNR} = -1.76$ dB. Hence, when using the Hanning window, a 1.76 dB decrease in the noise level was required to maintain the 80% detection success rate, compared to the Boxcar or no-window case.

If the same analysis is performed on the polyphase channelizer, and noting that the polyphase filter coefficients $h(n)$ have the same effect on the signal and noise power as the window weighting coefficients $w(n)$, then the effective change in the signal-to-noise ratio due to the polyphase filter coefficients compared to the FFT with a Boxcar window is

$$\Delta\mathit{SNR} = 10\log\left(\left[\sum_{n=0}^{NP-1} h(n)\right]^2\right) - 10\log\left(N \sum_{n=0}^{NP-1} h(n)^2\right). \tag{23}$$

Results for this expression are plotted in Figure 14 for different values of P, where $N = 2048$ and a Hanning window was used. Experimental values were also generated using the same experimental method as before (experiment two) except N was fixed and P varies from $P = 2$ to $P = 12$. There is good agreement between the predicted and experimental results.

The conclusion is that the difference in the detection noise levels shown for the two channelizers in Figure 13 is due to the 1.76 dB degradation caused by the Hanning window when used with the FFT plus the 0.3 dB advantage of the polyphase filter (with Hanning window) for $P = 12$, for a total difference of 2.06 dB.

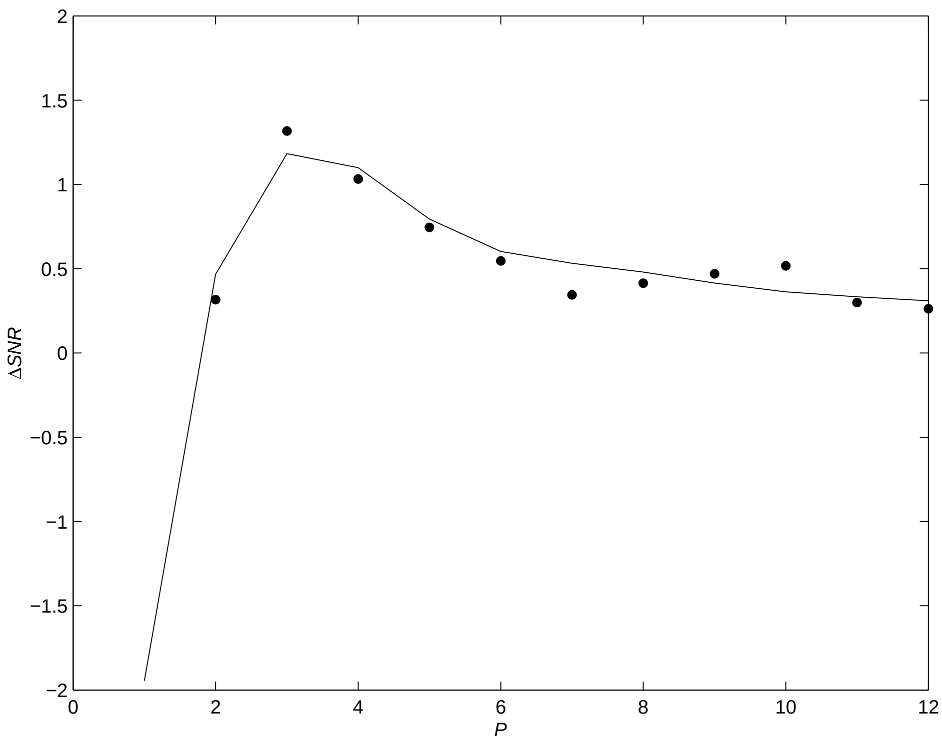


Figure 14: *The effect of P on the detection performance of the polyphase channelizer relative to the FFT channelizer with a Boxcar window. Positive values of ΔSNR denote an ability to detect signals at a lower SNR.*

3.3 Resolution of Two Signals

In the third experiment, the processing results of the two channelizers were compared using data containing two signals and *no* noise, where the second signal was incrementally adjusted in frequency until the two signals could no longer be resolved. The purpose of this experiment was to comparatively assess the ability to resolve two signals with smaller and smaller frequency separations.

The input data for this experiment consisted of two CW signals defined as

$$x(n) = e^{j(2\pi n f_1 + \theta_k)} + e^{j2\pi n f_2} \qquad \text{for} \;\; n = 0, 1, 2, ..., NP - 1 \tag{24}$$

where k is the trial number, θ_k is the initial phase of signal 1 which was varied between 0 and 2π radians, N is the FFT blocksize, and NP is the polyphase blocksize.

For this test, the frequency of the first CW signal was kept fixed, while the frequency of the second CW signal was varied to determine at what frequency spacing it was impossible to distinguish between the two signals (i.e. the two peaks merge to form one). The actual frequency values are shown in Table 1 along with the corresponding channel, given that the number of channels was $N = 2048$. The phase, θ_k, was also varied from 0 to 2π radians, and successful resolution was only considered to have occurred when both signals could be distinguished for all phase angles. The assessment was carried out for both channelizers, as well as for all five windows.

Table 1: *Signal frequency values*

f_1		f_2	
Freq	Chan	Freq	Chan
0.1001	205	0.0957	196
0.1001	205	0.0962	197
0.1001	205	0.0967	198
0.1001	205	0.0972	199
0.1001	205	0.0977	200
0.1001	205	0.0981	201
0.1001	205	0.0986	202
0.1001	205	0.0991	203
0.1001	205	0.0996	204

An example of using the Hanning window for both channelizers is illustrated in Figure 15 for $f_1 = 0.1001$ and $f_2 = 0.0957$. By inspection, the channelizer outputs are well behaved without any large spurious peaks – the only spurious peaks are those that can be attributed to sidelobe effects. This behaviour (no unexpected large spurious peaks) was true for all the two-signal results.

Figure 16 illustrates the change in the channel outputs as f_2 converges with f_1. Only the spectral region around the peaks is shown in order to preserve the plot detail. From the succession of plots from top to bottom, the two signals could be resolved until they

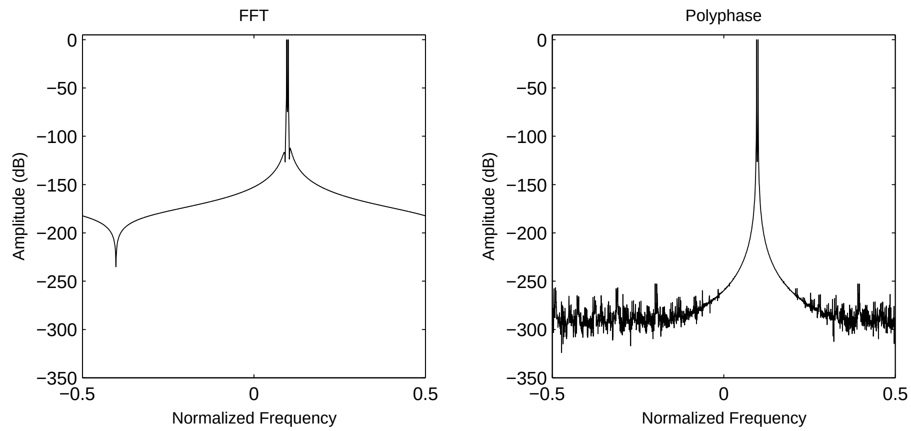


***Figure 15:** Results of channelizing data containing two CW signals using the Hanning window and with $f_1 = 0.1001$ and $f_2 = 0.0957$*

***Table 2:** Minimum Spacing Channel Between First and Second Signal*

Window	FFT	Polyphase
Boxcar	2	2
Bartlett	2	2
Hanning	3	2
Hamming	2	2
Blackman	3	2

were three channels apart for the FFT channelizer and two channels apart for the polyphase channelizer. At larger channel separations, the polyphase results are also more distinct – the valley between the peaks is deeper, and the fall-off away from the peaks more rapid (less leakage of signal power into adjacent channels).

The results for all windows and both channelizers are tabulated in Table 2. It was found that the minimum spacing between the two signals was two channels in order to achieve resolution, which is not surprising since at least one in-between channel is required to show the valley between the signal peaks.

For the polyphase channelizer, the main difference between windows was the amount of signal leakage into adjacent channels. As in the previous experiments, the Hanning and Blackman windows exhibited the best performance (i.e. in the spectral results the valley in-between the peaks were deeper and the drop-off away from the peaks more rapid).

The FFT approach was more sensitive to the choice of the phase θ_k when windows were used (except the Boxcar window) with $\theta_k \approx 0$ yielding the worst results. (By way of comparison, the polyphase approach was relatively unaffected by the choice of phase). The Hanning and Blackman FFT windows were the most adversely affected, which resulted in the minimum frequency spacing having to be increased by one channel. This is not a completely surprising result, since the Hanning and Blackman

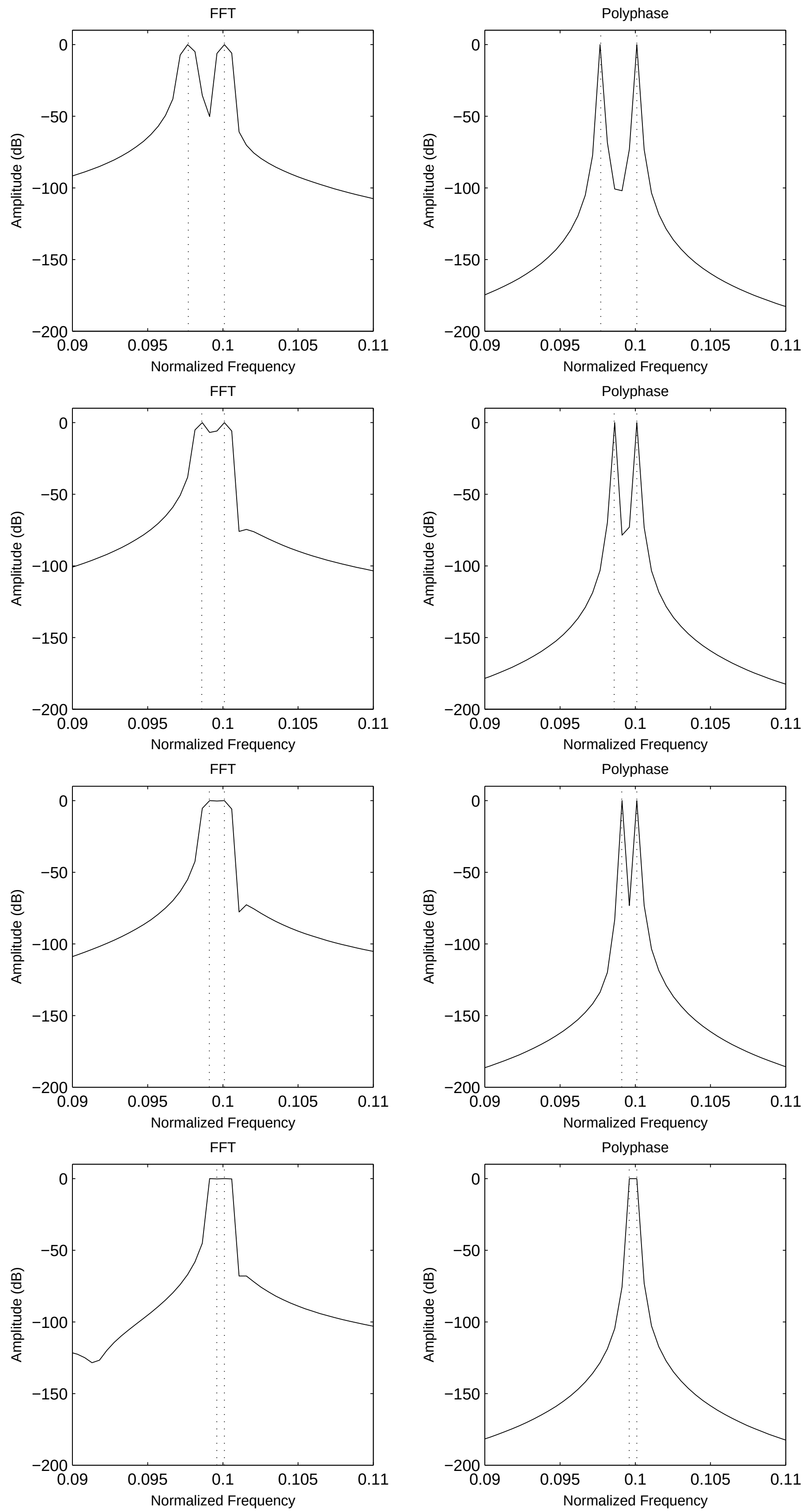


Figure 16: *Examples of channelizing data containing two CW signals using the Hanning window with $f_1 = 0.1001$ and (from top to bottom) $f_2 = 0.0977, 0.0986, 0.0991, 0.0996$ and for a phase $\theta_k = 0$. The vertical dotted lines correspond to the frequencies f_1 and f_2 (where $f_2 < f_1$).*

windows produce the widest channel bandwidths and so would be expected to have the worst resolution.

For modulated signals, the resolution results would be effected somewhat, particularly for signal bandwidths exceeding the channel bandwidth. The relative performances, however, would be expected to stay the same.

3.4 Two Signal Dynamic Range

In the last experiment, the dynamic range response of the FFT and polyphase channelizers was compared using data containing two fixed frequency signals plus noise. The signal level of one signal was then kept fixed and starting out with the same initial signal level, the second signal was decreased incrementally. For each incremental change, the noise level was adjusted until the weaker signal could only be detected 320 times out of 400 trials (an 80% probability of detection). The purpose of this experiment was to determine the minimum frequency spacing required to be able to uniquely resolve the two signals.

The input data for this experiment consisted of two CW signals plus noise, and was defined as

$$x(n) = e^{j(2\pi n 0.1001)} + s_2 e^{j2\pi n 0.0957+\theta_k} + \sigma\eta_k(n) \qquad \text{for} \;\; n = 0, 1, 2, ..., NP-1 \quad (25)$$

where k is the trial number, s_2 is the real-valued amplitude of the second signal, θ_k is the initial phase of the second signal chosen randomly between 0 and 2π using a uniform distribution, $\sigma\eta_k(n)$ is zero-mean random Gaussian noise with a variance of σ^2, $N = 2048$ is the FFT blocksize, and $NP = 2048 \times 12$ is the polyphase blocksize. The corresponding separation between signals was nine channels.

The experiment was performed by initially setting the signal amplitude to $s_2 = 1$. Beginning with some arbitrary initial estimate for the noise level σ (e.g. $\sigma = s_1$), 400 trials were carried out and the number of times the second signal could be successfully detected (i.e. the second highest peak in the channelizer spectrum corresponded to f_2) was counted. If this count exceeded 320, the noise level was increased, and if the count was less than 320, the noise level was decreased. Using the new noise level, the 400 trials were redone and the success rate tested again. This process was repeated over and over until the desired 80% probability of detection (320 successful detections) was achieved. Once the appropriate noise level was determined for $s_2 = 1$, then s_2 was decreased in 1 dB increments, and for each increment the new noise level was recalculated in the same manner as for $s_2 = 1$.

The above experimental procedure yields different results dependent on the channelizer and window function used. To simplify matters, the results for the FFT and polyphase channelizers were only determined using the Hanning window, and are shown in Figure 17. In this figure, the x-axis represents the strength of the second signal

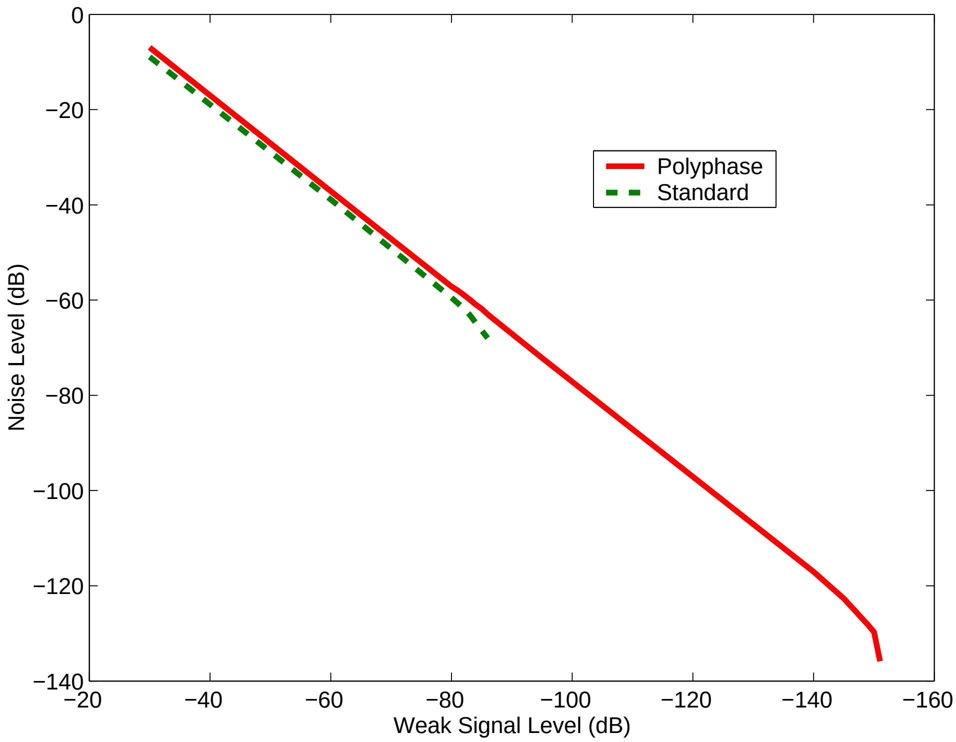


Figure 17: *Two Signal Dynamic Range*

($20 \log s_2$), and the y-axis represents the level of noise ($20 \log \sigma$) at which the 80% probability of detection occurs.

Examining the FFT and polyphase results, the results are cut-off for signal levels below approximately -85 dB for the FFT channelizer and -150 dB for the polyphase channelizer. Above these cut-off points, a fitted straight line approximation yields

$$(\textit{Noise Level})_{dB} = (\textit{Weak Signal Level})_{dB} + 21.15 \tag{26}$$

for the FFT results, and

$$(\textit{Noise Level})_{dB} = (\textit{Weak Signal Level})_{dB} + 23.35 \tag{27}$$

for the polyphase results. The polyphase channelizer is able to tolerate approximately 2 dB higher noise levels than the FFT channelizer, which is consistent with the 2.06 dB difference discussed in Section 3.2.

The cut-off points in 17 occur due to interference from the strong signal sidelobes so that regardless of how much the noise is reduced, the probability of detection for the weak signal drops below 80%. With no noise, the 80% probability of detection occurs when the weak signal level is -86 dB for the FFT channelizer and -150 for the polyphase channelizer.

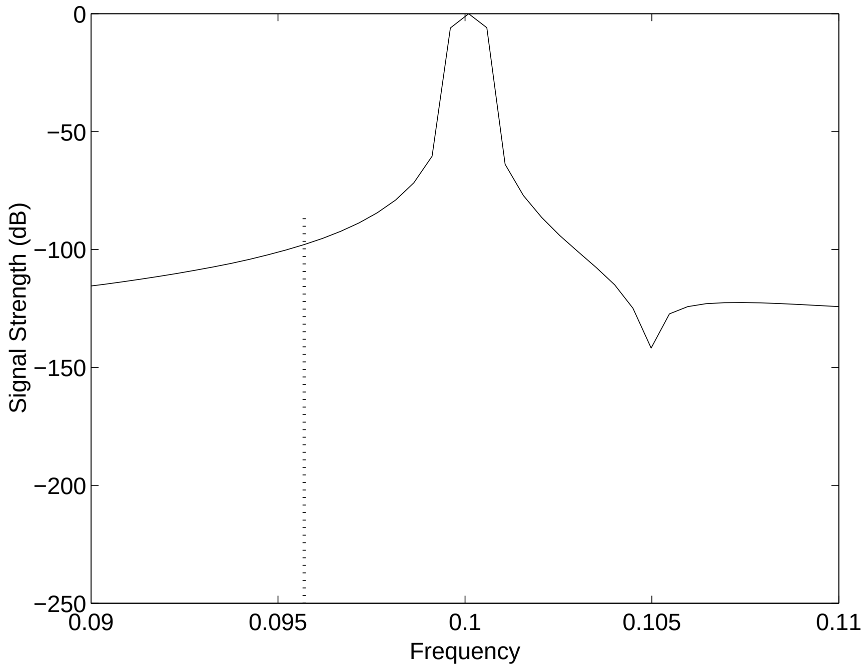


Figure 18: *Main Signal Sidelobe and Second Signal Peak, Standard FFT*

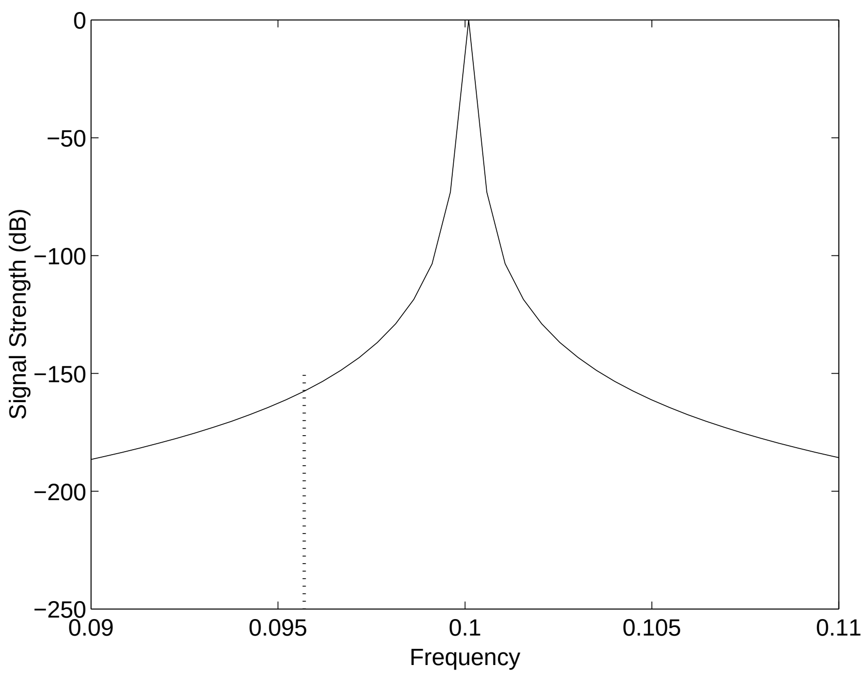


Figure 19: *Main Signal Sidelobe and Second Signal Peak, Polyphase FFT*

Figures 18 and 19 show examples of cases for the FFT and polyphase channelizers where the second signal has become undetectable due to the sidelobe interference, even though the weak signal level is greater than the sidelobe level. This can be understood if the interference is considered to be random in nature. For example, if the interference level and weak signal level in a channel are similar, then the interference will sometimes suppress the weak signal (destructive cancellation) making it undetectable. Hence, the signal level must be significantly greater than the interference level. Additionally, treating the sidelobe interference as Gaussian noise, then Equations (26) and (27) can be used to predict the weak signal levels required. Noting that the channel noise power will be $1/N$ times the input noise power, then the FFT noise level equation (26) can be modified as

$$(\textit{Channel Interference Level})_{dB} - 33.11 = (\textit{Weak Signal Level})_{dB} + 21.15 \tag{28}$$

and rewriting this expression in terms of the weak signal level then

$$(\textit{Weak Signal Level})_{dB} = (\textit{Channel Interference Level})_{dB} + 11.96. \tag{29}$$

Hence the weak signal must be 11.96 dB greater than the interference level to be detected 80% of the time. For a sidelobe level of -98 dB, the predicted weak signal level is -86 dB, which was exactly what was observed. Similarly for the polyphase channelizer,

$$(\textit{Weak Signal Level})_{dB} = (\textit{Channel Interference Level})_{dB} + 9.76. \tag{30}$$

The predicted weak signal level for a sidelobe level of -158 dB is -148 dB. The actual performance was 2 dB better (-150 dB) – a difference which may be due to the fact that Gaussian noise was not a perfect representation for the sidelobe interference.

In the end, even though these results are for a specific case, it is clear that the two signal dynamic range can be predicted using the measured sidelobe levels of the strong signal. Since the polyphase channelizer has significantly better sidelobe suppression, it has a significantly better two signal dynamic range than the FFT channelizer.

4. Conclusion

The availability of digital wideband receivers has motivated the development of digital filterbanks which subdivide the data into frequency channels to simplify the processing requirements. Two such channelizers were investigated in this report, namely the FFT based approach and the polyphase filter based approach. This investigation was performed in the context that the ultimate aim of the channelizer is to enable received signals to be extracted from the data for demodulation. The investigation also included the analysis of the effect of using five different window functions including Boxcar, Bartlett, Hanning, Hamming, and Blackman. Through experimental testing and theoretical analysis, the comparative advantages and disadvantages of each channelizer and the various windows were made clearly evident.

Based on the shape of the channel filter response in the frequency domain, the polyphase channelizer exhibits a flatter gain within the channel passband and significantly greater suppression of sidelobes outside the passband than does the FFT channelizer. Filter sidelobe effects can be reduced using window functions, with the Blackman and Hanning windows providing the greatest reduction. For the FFT channelizer, the use of windows to reduce the sidelobes also leads to an increase in the channel bandwidth. The channel bandwidth of the polyphase channelizer is unaffected by the choice of windows.

Testing against simulated wideband data containing a single signal without any noise essentially confirmed expectations based on the channel filter responses. Channelization was performed adequately by either channelizer and using any window, however undesirable leakage of the signal into channels not corresponding to the signal frequency did occur. This leakage was proportional to the filter sidelobes, so the comments made about sidelobe reduction and relative performances are also applicable here.

Using the same single signal scenario but adding varying levels of noise, the detection performances of the FFT and polyphase channelizers were the same when the Boxcar window was used. For any of the other windows, the detection performance of the FFT channelizer was reduced by 1 or 2 dB while the polyphase channelizer was unaffected. These remarks also hold true when the number of channels was varied.

Simulated wideband data was also generated containing two equal amplitude signals with a frequency spacing that was decreased in order to test the ability to resolve the two signals. A minimum separation of two channels (which is also the minimum possible spacing) was achieved for both channelizers when the Boxcar window was used. Performance was slightly worse for the FFT channelizer when the Blackman or Hanning window was used, while the polyphase channelizer was unaffected by the choice of window.

Finally, in the last test, wideband data was simulated using two signals with a fixed frequency spacing. The amplitude of one signal was reduced in steps and, at each step, sufficient noise was added so that the weaker signal could only be detected 80% of the time based on Monte Carlo simulations. The results show that this probability of detection was directly related to the signal-to-noise power ratio (SNR) of the weak signal, so that as the weak signal level was reduced, the noise level had to be proportionally reduced. The detection performance of the FFT channelizer was also degraded by windows requiring the noise level to be 2 dB less to achieve the desired probability of detection. This is the same effect observed in the single signal plus noise test.

The results of the last test also showed that detection of the weaker signal is ultimately limited by the signal leakage from the stronger signal even when there is no noise. Since the signal leakage is a consequence of the filter sidelobes, and the polyphase channelizer produces significantly lower sidelobes than the FFT channelizer, it was possible to detect the weaker signals at a much lower signal level using the polyphase channelizer. For example, for the simulation test setup that was used, the weak signal could be detected for signal levels as low as -150 dB relative to the strong signal when the polyphase channelizer with Hanning window was used, but only -86 dB when the FFT channelizer with the same window was used.

Overall, the analysis highlighted important aspects of the FFT and polyphase channelizers. The FFT channelizer has the advantage that for each block of N data values processed (where N is also the number of channels), the required number of computations is proportional to $N \log N$. The primary disadvantage is that the channel filter response is far from ideal with as much as a -4 dB change in gain from the center to the edge of the channel and high sidelobes (as much as -14 dB). The reduction in gain away from the center of the channel will reduce the effective SNR of signals whose center frequency is not aligned with the center frequency of the channel or modulated signals (whose instantaneous frequency will vary). The high side lobes significantly degrade the ability to detect and demodulate weak signals in the presence of strong interfering signals. Window functions can be used to reduce the sidelobes to more acceptable levels and improve performance in the presence of interference. Of the windows tested, the Blackman and Hanning windows were the best in this respect. The use of windows, however, does lead to a 1-2 dB reduction in detection performance and reduces the frequency resolution.

The polyphase channelizer has the advantage that the channel filter can be adjusted to better approximate the ideal response. Window functions can also be used to improve sidelobe response without any of the performance penalties associated with the FFT channelizer. Compared to the FFT channelizer, the result is as good or better detection performance for signals in noise, and substantially better performance for the detection of weak signals in the presence of strong signals. The main disadvantage is that larger data block sizes are required, $N \times P$, so that the processing requirements are proportional to $P \times N \log N$, where N is the number of channels and $N \times P$ is the data block size. Note that for $P = 1$, the polyphase channelizer is equivalent to the FFT channelizer, and as P increases, the channel filter response better approximates the ideal response.

Ultimately, the best choice is dependent on the application. In realtime applications where processing speed is critical, the FFT channelizer will often be the only choice. For applications requiring superior performance, the polyphase channelizer is the better choice, especially given the flexibility it allows in shaping the channel frequency response. The drawback is increased processing time and an increased observation window (i.e. more input samples required to produce each output sample). In the end, the choice between the FFT and polyphase channelizers comes down to speed versus performance.

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