Dynamic Digital Channelizer Based on Spectrum Sensing

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Abstract

The ability to efficiently channelize a received signal with dynamic sub-channel bandwidths is a key requirement of software defined radio (SDR) systems. The digital channelizer, which is used to split the received signal into a number of sub-channels, plays an important role in SDR systems. In this paper, a design of dynamic digital channelizer is presented. The proposed method is novel in that it employs a cosine modulated filter bank (CMFB) to divide the received signal into multiple frequency sub-bands and a spectrum sensing technique, which is mostly used in cognitive radio, is introduced to detect the presence of signal of each sub-band. The method of spectrum sensing is carried out based on the eigenvalues of covariance matrix of received signal. The ratio of maximum-minimum eigenvalue of each sub-band is vulnerable to noise fluctuation. This paper suggests an optimized method to calculate the ratio of maximum-minimum eigenvalue. The simulation results imply that the design of digital channelizer can effectively separate the received signal with dynamically changeable sub-channel signals.

Introduction

The concept of software defined radio (SDR) means that the same hardware architecture can be programmed or reconfigured to cope with any radio standard [1]. The digital channelizer is used to deal with the SDR signal composed of a large number of frequency division multiplexed (FDM) channels. It is employed to extract individual sub-channels from a digitized wideband input signal [2]. By extracting multiple narrowband sub-channels from the wideband input signal, it can efficiently reduce the sampling rate and bring convenience for the further base-band processing. The received signal of SDR system usually appears with several sub-channel signals with dynamically changeable bandwidths and band locations [3]. It leads to the requirement of dynamic digital channelizer.

A conventional way to realize channelization is feeding the received signal to a filter bank (FB). Many research achievements have been presented in recent years. The per-channel (PC) structure extracts each distinct sub-channel signal using a separate digital filter. It needs the
Proposed Structure of Digital Channelizer

There have been tremendous academic researches on the structure of digital channelizer [1–5, 16–19]. One of the widely used structure consists of an analysis section and synthesis section. The analysis section separates the received signal into several sub-bands. The output of each sub-band is decimated to reduce the sample rate. Then the synthesis section combines the adjacent sub-bands which contain the same sub-channel signal. Many previous works have achieved a remarkable performance using the analysis-synthesis structure. But few of them detail the method to detect the existence of signal in each sub-band.

This paper proposes a simple structure of dynamic digital channelizer based on spectrum sensing as shown in Fig 1. The received signal $X(z)$ is divided into $M$ sub-bands by a CMFB.
Since the bandwidth of each sub-band signal is \(1/M\) of the received signal, each output of the CMFB is oversampled by the factor \(M\).

\[
V_i(z) = X(z)H_i(z), \quad i = 0, 1, \ldots, M - 1
\]  

(1)

Instead of decimating immediately, the output data of each sub-band is directly fed to a spectrum sensing block to estimate the existence of signal. It can be found in the following section that the oversampled data is suitable rightly for the spectrum sensing method proposed in this paper. And then the adjacent sub-bands which contain signal are combined together, while the others will be ignored. The combined signal will be decimated, and the decimation factor is depending on the total number of combined sub-bands. In the real application, the structure can be further optimized by using a multistage decimation filter structure [20], but it is not the emphasis of this paper.

For the \(j\)th sub-channel signal, let \(Q_j^L\) and \(Q_j^U\) denote the lower and upper number of the included sub-bands. That is, the \(j\)th sub-channel signal can be reconstructed from the \(Q_j^U - Q_j^L + 1\) sub-bands data.

\[
Y_j(z) = \sum_{p = Q_j^L}^{Q_j^U} V_p(z) = \sum_{p = Q_j^L}^{Q_j^U} X(z)H_p(z)
\]  

(2)
It can be concluded that the bandwidth of the $j$th sub-channel signal $Y_j(z)$ is $1/M_j$ of the received signal, where $M_j = M/(Q_j^l - Q_j^r + 1)$. The needed sampling rate of the $j$th output can be reduced by decimation, which benefits the following base-band processing. Then a decimator is applied with decimation factor $M_j$. The final expression of the sub-channel signal is:

$$Y_j(z) = \frac{1}{M_j} X(z) \sum_{k=Q_j^r}^{Q_j^l} H_j(z) + \frac{1}{M_j} \sum_{l=1}^{M_j - 1} \sum_{k=Q_j^r}^{Q_j^l} X(zW_{M_j}^l) H_j(zW_{M_j}^l)$$

(3)

The first term is desired signal, and the second is aliasing one. The decimation factor of each final output is different and dynamically changeable.

### Modulated Filterbank

A common approach to realize the uniform filter bank (UFB) is to modulate a prototype filter (PF). The PF is a linear phase finite-length impulse response (FIR) filter. Many methods have been proposed to design the PF with linear phase. Ambede et al [16] propose a coefficient decimation method to obtain required FIR filter. The required PF is formulated by using interpolated FIR technique and single variable bisection type optimization technique in [21]. An optimization algorithm to design linear phase FB is presented in [22], which refers to interpolation technique.

A vital issue to design the CMFB is deciding the value of sub-band number $M$. An optional approach is making assumption that the minimum guard-band of all sub-channels is given beforehand [5]. Let $\omega_j^l$ and $\omega_j^r$ denote the lower and upper frequency limits of the $i$th sub-channel signal $X_i(z)$. $G_i$ is defined to be the width of the band between the $i$th and $(i + 1)$th channel and $G_{\min}$ is the minimum value among all $N$ guard-bands.

$$G_{\min} = \min_{i=0,1,\ldots,N-1} (\omega_{i+1}^l - \omega_i^r)$$

(4)

Then the sub-band number $M$ can be determined as follow.

$$M = \left\lfloor \log_2 \left( \frac{\omega_N^r - \omega_0^l}{G_{\min}} \right) \right\rfloor$$

(5)

Unlike the application of transmultiplexers or sub-band coding system, the aim of the PF design is not perfect reconstruction, but pass-band flatness and linear phase. To keep the integrity of the signal, the pass-band flatness of the CMFB should be guaranteed. $h(n)$ should be designed to meet the flatness condition, with a pre-specified tolerance $\delta$ and sub-band number $M$.

$$1 - \delta \leq |H_0(e^{j\omega})| + |H_0(e^{j\omega - \pi/M})| \leq 1 + \delta$$

(6)

The magnitude response of the PF designed by Parks-McClellan algorithm with the objective function discussed above is shown in Fig 2. Then the CMFB can be implemented by modulating the PF with linear phase.

$$h_k(n) = 2h_0(n) \cos \left[ \frac{\pi}{M} \left( k + 0.5 \right) \left( n - \frac{N - 1}{2} \right) + \frac{(-1)^k \pi}{4} \right]$$

(7)

Where $N$ is the order of $h_0(n), n = 0,1,\ldots,2mM - 1, k = 0,1,\ldots,M - 1$. Then a CMFB with $M$ branches is formed.
Spectrum Sensing Method

The task of spectrum sensing is to detect the existence of signal in the related frequency band. There are many algorithms to realize the spectrum sensing, including the match filtering, cyclostationary detection and energy detection. In this section, a spectrum sensing method based on eigenvalues is given. It can overcome the shortcoming of energy detection and achieve blind detection. Assume that the received signal gets the following form.

\[ x[n] = s[n] + w[n] \]

where \( s[n] \) is the received signal to be detected, \( w[n] \) is the additive white Gaussian noise (AWGN) with mean zero and variance \( \sigma_w^2 \), and \( n \) is sample index. Note that \( s[n] = 0 \), when there is no signal contained in the receiver. Therefore, the spectrum sensing problem is equivalent to distinguishing between two hypotheses: \( H_0 \), signal absent, and \( H_1 \), signal present.

\[
\begin{align*}
H_0 : x[n] &= w[n] \\
H_1 : x[n] &= s[n] + w[n]
\end{align*}
\]

It has been known from the former section that each sub-band data output is over-sampled at least by a factor \( M \). Consequently, the oversampled method can be fittingly used to construct the covariance matrix. Assume that \( x_i[n] \), \( i = 1, 2, \ldots, M \) denotes the output data of the \( i \)th sub-band, where \( n = 1, 2, \ldots, L \). \( L \) is the length of the dataset and \( L = NM \). A resampled data set can
be defined as follow.

\[ x_i[n] = x_i[nM + j - 1], j = 1, 2, \ldots, M \]  

(10)

Where the subscript \( i \) denotes the number of sub-band signal, and superscript \( j \) denotes sample time of the resample signal. Then a data matrix \( x_i \) can be expressed as

\[ x_i = [x_i^1, x_i^2, \cdots, x_i^M] \]  

(11)

The covariance matrices of each sub-band data are obtained.

\[ R_i^x = E[x_i x_i^T] = x_i x_i^T / N, i = 1, 2, \ldots, M \]  

(12)

Assume that noise and signal are uncorrelated.

\[ R_i^s = AR_i^s A^T + \sigma_i^2 I \]  

(13)

Where \( R_i^s \) denotes the signal covariance matrix of the \( i \)th sub-band. \( \sigma_i^2 I \) represents the covariance matrix contains the noise. A spectrum sensing algorithm, based on the maximum-minimum eigenvalue, was proposed in [12]. \( \lambda_i^{\text{max}} \) and \( \lambda_i^{\text{min}} \) are the maximum and minimum eigenvalue of the matrix \( R_i^s \). Then, the spectrum sensing decision can be made as follow: if \( \lambda_i^{\text{max}} / \lambda_i^{\text{min}} > \alpha \), signal exists in the corresponding sub-band; otherwise, signal does not exist, where \( \alpha > 1 \) is a threshold. The selection of the threshold \( \alpha \) is a key component of the spectrum sensing algorithms.

Let \( P_d \) be the probability of detection, and \( P_f \) be the probability of false alarm. the threshold \( \alpha \) can be calculated by the follow [12, 14].

\[ \alpha = \left( \frac{\sqrt{N} + \sqrt{M}}{\sqrt{N} - \sqrt{M}} \right)^2 \left( 1 + \frac{(\sqrt{N} + \sqrt{M})^{-2/3}}{(NM)^{1/6}} F_{\alpha}^{-1}(1 - P_f) \right) \]  

(14)

\( F_{\alpha} \) is the cumulative distribution function of the Tracy-Widom distribution of order 1. The value of \( F_{\alpha} \) can be looked up from tables [23].

In the application of channelizer, each sub-band signal is filtered by a bandpass filter. Moreover, the multipath propagation and fluctuation of the noise may cause remarkable effect on the eigenvalues of each sub-band signal. For example, an infinitesimal \( \lambda_i^{\text{min}} \) may appear in the \( i \)th sub-band. Then a small \( \lambda_i^{\text{max}} \) will cause a ratio bigger than the threshold, though \( \lambda_i^{\text{max}} \) is actually produced by noise and the sub-band holds no useful signal. The selection of \( \lambda_i^{\text{min}} \) and \( \lambda_i^{\text{max}} \) should take an overview consideration of the whole sub-band signals.

According to the discussion above, the eigenvalue-based spectrum sensing problem boils down to the two hypotheses.

\[ \begin{align*}
H_0 & : x[n] = w[n] & \lambda_i^{\text{max}} / \lambda_i^{\text{min}} \leq \alpha \\
H_1 & : x[n] = s[n] + w[n] & \lambda_i^{\text{max}} / \lambda_i^{\text{min}} > \alpha
\end{align*} \]  

(15)

where \( \lambda_i^{\text{max}} \) and \( \lambda_i^{\text{min}} \) is corresponding to the signal component and noise of each sub-band, respectively. This paper presents a novel selection of \( \lambda_i^{\text{max}} \) and \( \lambda_i^{\text{min}} \) to optimize the detection performance. By dividing the received signal into \( M \) sub-bands, eigenvalues of each sub-band signal are obtained, \( \lambda_i, i = 1, 2, \cdots, M; j = 1, 2, \cdots, M \). Subscript \( i \) denotes the sequence number of sub-band, and superscript \( j \) is related to eigenvalue of the \( i \)th sub-band. \( \lambda_i \) is defined as the
average value of the $M$ eigenvalues of the $i$th sub-band signal.

$$\bar{\lambda}_i = \frac{1}{M} \sum_{j=1}^{M} \lambda_{ij} \quad (16)$$

Then $M$ maximum eigenvalues of each sub-band signal are collected. These $M$ maximum eigenvalues can be regarded as the main component of the sub-bands output, either signal or noise. On the other hand, it is concluded from the design of analysis FB that at least one of the sub-bands contains noise only. Therefore, the minimum of the $M$ average eigenvalues can be a reasonable estimate of the noise component within the received signal.

The ratio of maximum-minimum eigenvalue to determine the presence of signal for each sub-band can be optimized as follow.

$$\alpha_i = \frac{\max_{j=1,2,\ldots,M} \lambda_{ij}}{\min_{i=1,2,\ldots,M} \lambda_{ij}}, \quad i = 1, 2, \ldots, M \quad (17)$$

If $\alpha_i > \alpha$, there is signal resides in the $i$th sub-band. Otherwise, it contains noise only. The steps to realize the dynamic digital channelizer can be summarized as follow.

1. Design a CMFB by modulating a linear phase PF. The sub-band number of the CMFB is decided by the minimum guard-band of the received signal, as expressed in Eq (5).
2. Divide the received signal into $M$ frequency bands. The signal of each band is oversampled by a factor $M$.
3. Construct data covariance matrix of each sub-band signal, using the oversampled signal.
4. Detect the presence of useful signal in each band by eigenvalue-based spectrum sensing technique.
5. Combine the adjacent bands which contain signal. Decimate the signal according to the combined sub-band number.

**Simulation**

The functionality of the proposed structure of digital channelizer is verified in this section. A received signal with 4 sub-channels is shown in Fig 3(A). The received signal is divided into $M = 16$ sub-bands by CMFB, determined by the minimum guard-band. Then the detection of the existence of signal in each sub-band is implemented by eigenvalue-based spectrum sensing method.

The false alarm probability is set to $P_f = 0.05$. According to Eq (14), the detection threshold is $\alpha = 1.29$. And the radio used to detect the existence of signal of each sub-band is depicted in Table 1.

It can be inferred from Table 1 that the 2nd, 4th~6th, 8th~9th and 12th~15th sub-bands contain the consecutive sub-band signal, respectively. Combine the adjacent bands, the channelization result can be found in Fig 3(B)–3(E).

Another received signal with 3 sub-channels is depicted in Fig 4(A). The detection parameters are set the same as before. Then the 2nd~4th, 7th~12th and the 15th sub-bands are combined together to form the final sub-channel signal, concluded form Table 2. The results are shown in Fig 4(B)–4(D).
The simulation results shown above indicate that the proposed structure of digital channelizer can split the received signal into multiple sub-channels effectively and the eigenvalue-based spectrum sensing technology can easily detect the existence of signal in each divided sub-band.

![Image of spectra](image)

**Fig 3.** (a) Spectrum of Received Signal Containing 4 Sub-channels, (b)-(e) Channelized Signals Using Proposed Structure.

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| Band number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-------------|----|----|----|----|----|----|----|----|
| ratio       | 1.07 | 747.73 | 1.00 | 14.12 | 817.95 | 123.00 | 1.00 | 386.00 |
| Band number | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| ratio       | 370.87 | 1.03 | 1.05 | 83.27 | 848.71 | 136.62 | 35.78 | 1.03 |

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The simulation results shown above indicate that the proposed structure of digital channelizer can split the received signal into multiple sub-channels effectively and the eigenvalue-based spectrum sensing technology can easily detect the existence of signal in each divided sub-band.
The design of digital channelizer in this paper can fill the requirement of SDR system to dynamically channelize the received signal.

Conclusions

A novel structure of dynamic digital channelizer, which consists of analysis and synthesis section as mentioned in the previous work, is proposed. The proposed structure introduces spectrum sensing technique to confirm the presence of signal in each band of analysis section.

Table 2. Ratio of maximum-minimum eigenvalue of each sub-band data of the received signal in Fig 4(A).

| Band number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| ratio       | 1.12| 586.27| 310.66| 84.92| 1.00| 1.07| 27.56| 127.59|
| Band number | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
| ratio       | 126.58| 25.93| 29.70| 25.06| 1.20| 1.03| 952.15| 1.05|

Fig 4. (a) Spectrum of Received Signal Containing 3 Sub-channels, (b)–(d) Channelized Signals Using Proposed Structure.

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Unlike the previous work, the oversampled signals are fed to spectrum sensing section directly, instead of decimation. This process is fittingly convenient for the eigenvalue-based spectrum sensing. Due to requiring no prior knowledge of signal or noise, the eigenvalue-based method can realize blind spectrum detecting. Given the minimum guard-band of the received signal to determine the sub-band number of the modulated FB, the structure proposed in this paper can achieve dynamic digital channelizer for SDR systems.

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Author Contributions

Conceived and designed the experiments: JH ZH. Performed the experiments: JH ZZ. Analyzed the data: ZD ZH. Contributed reagents/materials/analysis tools: JH ZZ. Wrote the paper: JH. Prepared the equipment needed for experiment: ZD.

References

1. Panicker MR, Vinod AP, Lai EMK, Omondi A. Filter bank channelizers for multi-standard software defined radio receivers. J Sign Process Syst. 2011; 62:157–171.
2. Panicker MR, Vinod AP. Reconfigurable low area complexity filter bank architecture based on frequency response masking for nonuniform channelization in software radio receivers. IEEE Transactions on Aerospace and Electronic Systems. 2011 Apr; 47(2):1241–1255.
3. Li B, Ge LD, Zheng J. Efficient dynamic channeliser based on nonuniform filter banks. European Transactions on Telecommunications. 2008 Apr; 19(3):273–283.
4. Darak SJ, Vinod AP, Lai EMK. A low complexity reconfigurable non-uniform filter bank for channelization in multi-standard wireless communication receivers. Journal of Signal Processing Systems for Signal Image and Video Technology. 2012 Jul; 68(1):95–111.
5. Abu-Al-Saud WA, Stüber GL. Efficient wideband channelizer for software radio systems using modulated pr filterbanks. IEEE transactions on signal processing. 2004; 52(10):2807–2820.
6. Xie XM, Li L, Shi GM, Peng B. Method for signal decomposition and denoising based on nonuniform cosine-modulated filter banks. Progress in Natural Science-Materials International. 2008 Oct; 18 (10):1293–1298.
7. Yucek T, Arslan H. A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Communications Surveys and Tutorials. 2009; 11(1):116–130.
8. Atapattu S, Tellambura C, Jiang H. Energy detection based cooperative spectrum sensing in cognitive radio networks. IEEE Transactions on Wireless Communications. 2011 Apr; 10(4):1232–1241.
9. Zhang W, Malik RK, Ben Letaief K. Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks. IEEE Transactions on Wireless Communications. 2009 Dec; 8 (12):5761–5766.
10. Chen HS, Gao W, Daut DG, editors. Signature based spectrum sensing algorithms for IEEE 802.22 wran. IEEE International Conference on Communications (ICC'07); 2007; Glasgow, Scotland.
11. Sutton PD, Nolan KE, Doyle LE. Cyclostationary signature in practical cognitive radio applications. IEEE Journal on Selected Areas in Communications. 2008; 26(1):13–24.
12. Zeng Y, Liang Y-C. Eigenvalue-based spectrum sensing algorithms for cognitive radio. IEEE Transactions on Communications. 2009 Jun; 57(6):1784–1793.
13. Zeng Y, Liang Y-C. Spectrum-sensing algorithms for cognitive radio based on statistical covariances. IEEE Transactions on Vehicular Technology. 2009 May; 58(4):1804–1815.
14. Penna F, Garello R, Spirito MA. Cooperative spectrum sensing based on the limiting eigenvalue ratio distribution in wishart matrices. IEEE Communications Letters. 2009 Jul; 13(7):507–509.
15. Zeng Y, Liang Y-C, Hoang AT, Zhang R. A review on spectrum sensing for cognitive radio: Challenges and solutions. Euraip Journal on Advances in Signal Processing. 2010:1–15.
16. Ambede A, Smitha KG, Vinod AP. A low-complexity uniform and non-uniform digital filter bank based on an improved coefficient decimation method for multi-standard communication channelizers. Circuits Systems and Signal Processing. 2013 Dec; 32(6):2543–2557.
17. Harris F, Chen XF, Venosa E. A novel pr channelizer-based architecture for estimation and correction of timing and gain mismatches in two channel ti-adcs. In: Garimella A, Purdy CC, editors. 2012 IEEE 55th international midwest symposium on circuits and systems. Midwest symposium on circuits and systems conference proceedings 2012. p. 1140–1143.

18. Vinod AP, Lai EMK, A.B P, editors. A reconfigurable multi-standard channelizer using qmf trees for software radio receivers. In proceedings of 14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communication; 2003.

19. Bres CS, Zlatanovic S, Wiberg AOJ, Radic S. Reconfigurable parametric channelized receiver for instantaneous spectral analysis. Optics Express. 2011 Feb; 19(4):3531–3541. doi:10.1364/OE.19.003531 PMID: 21369177

20. Michael N, Vinod AP, Moy C, Palicot J. Design strategy for clocking and runtime parametrization in the channelization accelerator of multistandard radios. Journal of Signal Processing Systems. 2015; 78 (2):171–177.

21. Rk Soni, Jain A, Saxena R. A design of ifr prototype filter for cosine modulated filterbank and transmultiplexer. International Journal of Electronics and Communications. 2013; 67:130–135.

22. Wang M, Wan J, Zhao Y. Design of linear phase nonuniform filter banks with interpolated prototype filters. In: Guo H, editor. 2012 international workshop on information and electronics engineering. Procedia engineering. 29;2012. p. 435–440.

23. Johnstone IM. On the distribution of the largest eigenvalue in principle components analysis. Annals Statistics. 2001; 29(2):295–327.