FIR Filters for LTE-Advanced Technology

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Long-Term Evolution-Advanced (LTE-A) technology was rolled out to meet the increase in the demand for data. The key mechanism of LTE-A, carrier aggregation provides wide bandwidth to meet this increased data requirement. Most of the smartphones support carrier aggregation to offer wide bandwidth. The hardware requirements of these digital systems are also modified to meet the specifications like small area, less power consumption, small size, etc. Digital filters form the core component in these digital systems. The paper applies the design of the Finite Impulse Response (FIR) digital filters to the devices that support carrier aggregation.

***Keywords*:** Digital filters, Finite Impulse Response (FIR) filters, Infinite Impulse Response (IIR) filters, Wavelets, Carrier aggregation, Long-Term Evolution-Advanced (LTE-A), Narrow transition band filters

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Introduction

Carrier aggregation is one of the important mechanisms of the Long-Term Evolution-Advanced (LTE-A) systems. The component carriers of same or different bandwidth are aggregated to provide larger bandwidth to satisfy the increased data rate (Rappepat *et al*., 2010; Rahat and Asad, 2012; and Jan *et al.*, 2013). The component carriers may be from the same frequency band or from different frequency bands. The aggregated bandwidth may be as wide as up to 100 MHz by aggregating about maximum of five different carriers of about 20 MHz each to provide a data rate of 1 Gbps (Alastair, 2012; Suresh *et al*., 2016; and Pushpavathi and Kanmani, 2020). It consists of subbands with the center frequency of carriers being separated by 300 kHz or it multiples along with the guard band (Rappepat *et al.*, 2010; and Ibraheem *et al.*, 2012). As an improvement of the LTE (or 4G), LTE-A is a multicarrier system. Multi-Carrier Modulation (MCM) is used as an alternate choice for the Orthogonal Frequency Division Multiplexing (OFDM) of LTE systems to meet the requirements (Lei *et al*., 2020).

Lots of different methods like cyclic prefix OFDM, OFDM Access (OFDMA), and Wavelet-Orthogonal Frequency Division Multiple Access (WOFDM) are found in literature to reduce Inter-Channel Interference (ICI) or Inter Symbol Interferences (ISI)

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(Lei *et al.*, 2020) in these multicarrier systems. Among band leakage signals, nonlinear distortions and frequency offsets are some of the issues that impact the performance of the system. Hence different modulation schemes like Filter Bank Multicarrier (FBMC) (Farhang-Boroujeny, 2011; Han *et al.*, 2017; and Lei *et al.*, 2020), Generalized Frequency Division Multiplexing (GFDM) (Michailow *et al.,* 2012; and Lei *et al.*, 2020), and Universal Filtered Multicarrier (UFMC) (Vakilian *et al.,* 2013; and Lei *et al.*, 2020) gave rise to the advancement of digital filters.

Digital filters are used for the design of the filters that are not possible using analog filters (Bansal *et al.*, 2018). The authors discussed different techniques for design of Finite Impulse Response (FIR) filters and analyzed different factors that contribute to the implementation of the filter in multicarrier system. To achieve good filtering, the flat magnitude response in the desired range of the signal along with the linear phase characteristics should be met (Lei *et al.*, 2020). Digital FIR filters are commonly used for wireless communications due to their linear phase characteristics and ability to establish their structure. Intermodulation effects due to the non-linearity of the components are reduced maintaining low receiver de-sense using the FIR filter (Hamed *et al.*, 2015). Subhabrata and Abhijith (2019a) discussed the narrow band digital filters for OFDM systems under various QAM channel conditions. Thomas and Michael (2011) studied the use of the dyadic filters for LTE that is built using the IIR filter approaches. Cortes *et al.* (2016) evaluated the use Bulk Acoustic Wave (BAW) filter on the functioning of the UE in LTE.

Digital FIR filters are commonly designed using three methods, namely, rectangular window method, frequency sampling method and the optimization method (Lawrence and Bernad, 1998). We considered the frequency sampling method of designing the FIR filter as applied to the LTE-A standard. This method is adopted as it can be used with the frequency sampling structure. The coefficients of the structure are the frequency response values of the filter sampled at N number of points that are equally spaced with N being the order of the filter. Also, the filter can be realized with very few non-zero samples (Chen and Yu, 2000).

The paper is organized as follows: First, the paper gives a brief description of frequency sampling method followed by narrow transition band filter. Then it presents an analysis of simulation results and discussion. Finally, the paper ends with conclusion.

Methodology

Frequency Sampling Method

In frequency sampling method, the frequency response of the filter is evaluated by sampling the desired frequency response at N equally spaced points. Let $H[k]$ with $k = 0, 1, \ldots, N - 1$ be the N uniformly spaced samples of desired frequency response, $H_{desired}(\omega)$, (Pushpavathi and Kanmani, 2018) given by Equation (1):

$$H[k] = \left|H_{desired}(\omega)\right|_{\omega=\frac{2\pi}{N}k} e^{-j\frac{2\pi(N-1)}{N}k} \qquad k = 0,1,2..,N-1 \qquad ...(1)$$

Taking Inverse Discrete Fourier Transform (IDFT) of $H[k]$, the filter coefficients of the desired FIR filter is as shown by Equation (2) (Pushpavathi and Kanmani, 2018):

$$h[n] = \frac{1}{N}\sum_{k=0}^{N-1} H[k]e^{j2\pi nk/N} \qquad n = 0,1,...,N-1 \qquad ...(2)$$

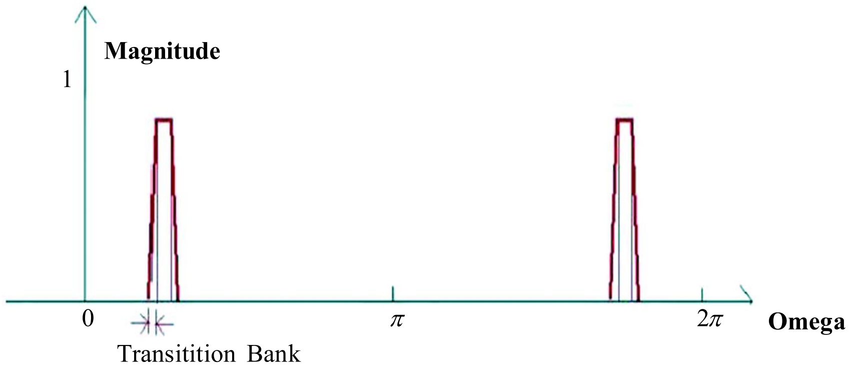
This method does not require solving the integration as in rectangular window method (Pushpavathi and Kanmani, 2018). Thus computation complexity of this method is easier and is the same for any arbitrary frequency response.

Narrow Transition Band Filters

Digital filters of higher order are used to achieve the narrow transition band. These filters may find their applications in the User Equipment (UE) that support carrier aggregation. The aggregated bandwidth consists of a number of sub-channels, each filtered with suitable filters.

Also, as LTE-A is a multicarrier system, the performance of using the narrow transition band is considered. Literature review shows that narrow transition band digital filters under different QAM conditions are studied by Subhabrata and Abhijith (2019) for OFDM systems. Subhabrata and Abhijith (2019) considered the interpolated band pass filtering to design the narrow transition band filter. They obtained an expression for the optimal interpolation factor to achieve a narrow transition band. The desired filter response is shown in Figure 1.

Figure 1: Narrow Band Filter Response with Small Transition Band



We applied the frequency sampling method to design the narrow transition band FIR filter for the LTE-A standards as the number of non-zero samples is very less and depends on the passband. The use of the frequency sampling method to implement the narrow transition band filter is advantageous as it can be easily realized using the frequency sampling structure (Pushpavathi, 2020). The narrow band filter characteristic is studied considering the ideal case with sharp transition and by introducing a small transition band.

Due to Gibb's phenomenon, lots of ripples are present in the stopband of the filter. To minimize the stopband spectral components, a small transition band is introduced in the frequency response of the desired filter (Pushpavathi, 2020). Given the frequency response, the frequency sample $H[k]$ is computed. The impulse response is obtained using Equation (2). The designed filter response is then obtained using Equation (3) (Pushpavathi, 2020). The resulting response is then compared with the design of sharp transition band.

$$H(\Omega) = \sum_{n=0}^{N-1} h(n) e^{-j\Omega n} \qquad \text{...(3)}$$

Results and Discussion

Simulation

ST-Ericsson introduced Thor M7450, a platform for LTE-A (Jan *et al.*, 2013). It is a System on Chip (SoC) that supports 10 MHz + 10 MHz, 5 MHz + 10 MHz and 5 MHz + 5 MHz carrier aggregation along with a number of different band combinations. It supports both TDD and FDD LTE along with all 3 GPP frequency bands (Brian, 2013). Vakilian *et al.* (2013) discussed that the data stream of the user may be divided into substreams, and a pulse-shaping filter with Fast Fourier Transform (FFT) size of 128 was used to minimize the out-of-band leakage in the frequency band. Prashant (2012) studied that from the different bands available, band 40 with the frequency ranging from 2,300 MHz-2,400 MHz is used in our country, which allows a bandwidth of up to 100 MHz supporting channel bandwidth of 5, 10, 15 or 20 MHz. We considered the FFT sizes of 128 and 1,024 for the bandwidths of 1.25 MHz and 10 MHz, respectively (Jim, 2007).

The FIR filter design using frequency sampling method is implemented for the low pass filter and the narrow transition band filter considering the order of filter to be equal to the FFT size.

Frequency Sampling Method

Let Equation (4) (Pushpavathi and Kanmani, 2018) represents the response of the ideal low pass filter. Let the cut-off frequency be $\omega_c = \pi/2$

$$H_{desired}(\omega) = \begin{cases} 1 \text{ if } |\omega| \le \omega_c \\ 0 \text{ if } \omega_c < |\omega| < \pi \end{cases} \qquad \text{...(4)}$$

N equally spaced frequency samples, $H[k]$ are found from Equation (1) by uniformly sampling the desired frequency response over an interval of $(0, 2\pi]$. A few of the frequency samples obtained will be zeroes. Considering the frequency samples as the Discrete Fourier Transform (DFT) of filter impulse response, filter coefficients $h(n)$ are obtained through IDFT of $H[k]$, as given by Equation (2). Using Equation (3), the designed frequency response is obtained and shown in Figures 2 and 4 for the order of the filter, $N = 128$ and 1,024 (Jim, 2007) respectively. Figures 3 and 5 display the pole-zero plots for the two cases, respectively.

Figure 2: Magnitude Response of FIR Filter for $N = 128$

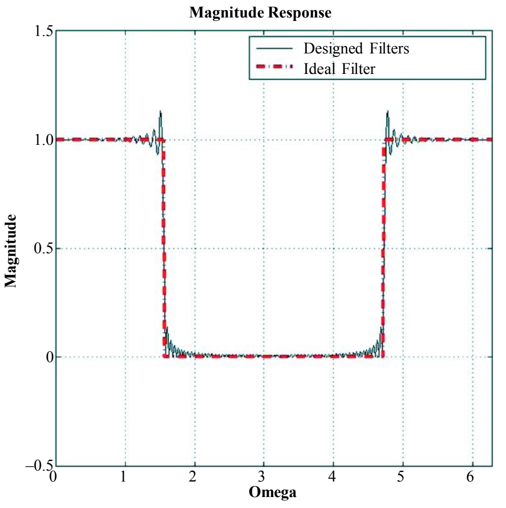


Figure 3: Pole-Zero of FIR Filter for $N = 128$

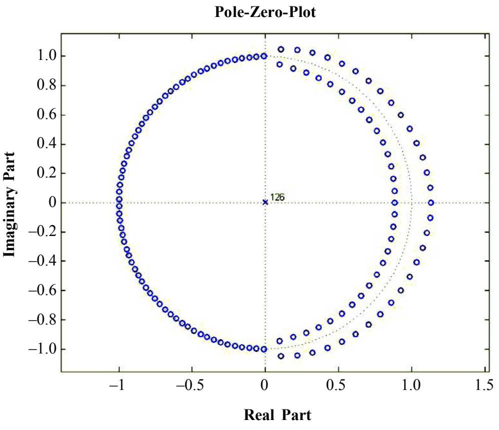


Figure 4: Magnitude Response of FIR Filter with $N = 1,024$

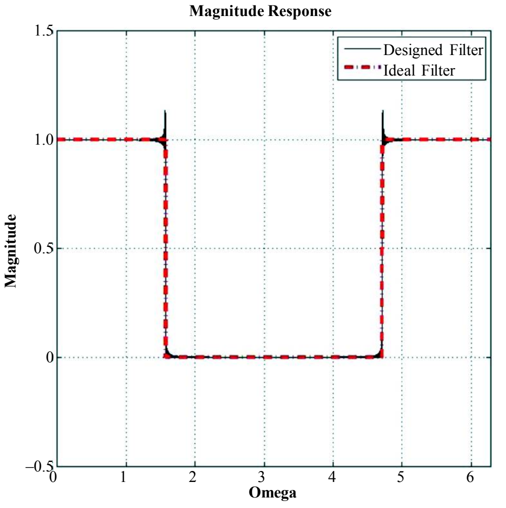


Figure 5: Pole-Zero of FIR Filter with $N = 1,024$

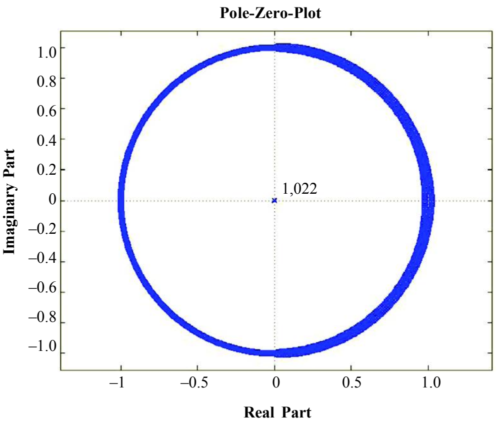


Table 1 shows the variation of the Mean-Squared-Error (MSE) along with the Overshoot (OS) (Jim, 2007; and Pushpavathi and Kanmani, 2018) considering the filter order, N suitable for the specified bandwidth for the low pass filter using frequency sampling method.

Table 1: Variation of the Mean-Squared-Error Along with the Overshoot

N	BW (MHz)	MSE	OS
128	1.3	0.0121	1.1327
256	2.5	0.0060	1.1347
1,024	10	0.0015	1.1361

It is observed that the mean square error is reduced with the increase in the order of the filter, while there is very small change in the overshoot. The filter is observed to be stable and satisfies the linear characteristic.

Narrow Band Filter

We considered the frequency sampling method to implement the narrow transition band filter. The desired frequency response of the ideal narrow transition band filter is sampled at N equally spaced samples as in Equation (1). We introduced a small transition band in the frequency response of the filter desired. The transition band width is made equal to the sampling resolution, $2\pi/N$. The magnitude of filter coefficient in the transition band (T_a) is chosen to have the value such that the spectral content is low (Pushpavathi, 2020). The frequency response obtained is shown in Figures 6 and 7 for the order of the filter,

Figure 6: Plot of Frequency Response for N = 128

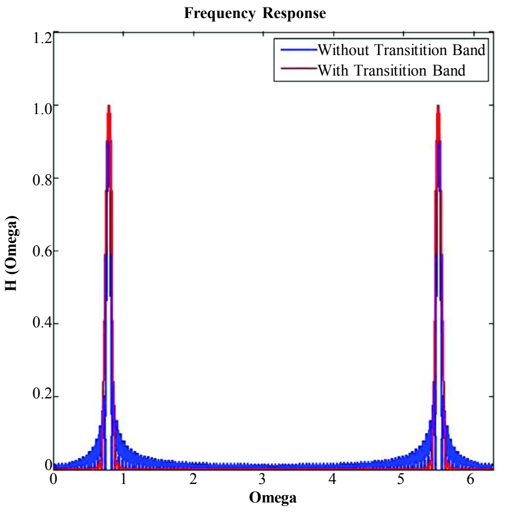
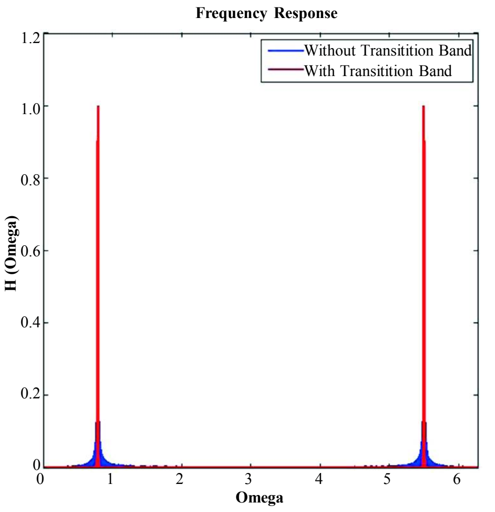


Figure 7: Pole of Frequency Response for N = 1,024



N = 128 and 1,024. Table 2 shows the spectral contents in the passband and the stopband of the filter response (Jim, 2007; and Pushpavathi, 2020).

Table 2: Spectral Content in Passband and the Stopband

Order of Filter	BW (MHz)	Stopband		Passband	
		Sharp Transition	Smooth Transition (T_a = 0.5)	Sharp Transition	Smooth Transition (T_a = 0.5)
128	1.3	4.5190	0.1844	5.8207	8.1193
256	2.5	5.5866	0.1864	5.8185	8.1193
1,024	10	7.7191	0.1870	5.8166	8.1193

We found that stopband spectral content is reduced with the introduction of the small transition band with magnitude of filter coefficient, T_a, while it is increased in the passband.

Conclusion

The paper studies digital FIR filter design from the frequency sampling method as applied to the LTE-A standard. Its use in the implementation of the narrow transition band filter is considered. As most of the filter coefficients are zeros, realizing the filter using frequency sampling structure is easier. It is noted that with the increase in the filter order, the mean square error is reduced and the transition band became steeper with fewer ripples in the stopband. This ensures that good filtering may be expected. Hence, higher order FIR filters with narrow transition band could be used in the devices that support LTE-A standards for carrier aggregation. ⏮

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Reference # 59J-2021-10-02-01