



POWER OPTIMISATION FOR ADAPTIVE EMBEDDED WIDEBAND RADIOS

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Pham Hung Thinh

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6.1 Introduction to Spectral Leakage Filtering

This chapter is concerned with the OFDM spectral leakage challenge for OFDM-based CRs. OFDM signals typically cause large amounts spectral leakage, whereas CRs demand a shaped spectrum confined within the allocated channel in order to reuse free spectral bands without causing ICI to other users occupying adjacent bands. Some recent OFDM-based standards are defined with the requirements on spectral leakage that are extremely stringent in an effort to avoid ICI. Spectral leakage filtering may cause some effects on transmitted signals that lead to a reduction in the effective timing guard. Therefore, the implementations of spectral leakage filtering need to be able to take into account the parameters of the underlying OFDM signal and its channel characteristics to avoid causing the negative effects on the transmitted signal such as distortion and ISI.

In this chapter, a novel method that embeds baseband filtering within a cognitive radio (CR) architecture, is proposed. The method is able to meet the specification for the most stringent 802.11p SEM, meet the specification of the 802.11af strict SEM requirement, and furthermore is able to allow ten additional 802.11af sub-carriers to occupy a single basic channel without violating SEM specifications. In addition, the method can adaptively change filter performance according to the transmission power to reduce the computation cost while guaranteeing that the emission spectrum remains smaller than the allowed spectral leakage. The method, performed at baseband, relaxes the otherwise strict RF front-end requirements. This allows the RF subsystem to be implemented based upon much less stringent 802.11a designs, which can significantly reduce total cost.

This section firstly analyses the spectral leakage specification of two recent OFDM-based standards (i.e., 802.11p, 802.11af) together with their defined parameters and channel characteristics to determine their filtering requirements. Then, the state of the art spectral leakage filtering methods are studied and applied in order to show whether those methods are able to meet the strict spectral leakage requirements.

Generally, the PHYs of 802.11p and 802.11af are largely inherited from the well-established 802.11a and 802.11ac OFDM PHYs, respectively. The major PHY parameters of these standards are presented in Table 6.1. However, the new standards perform on different channel and in different environment leading to some very strict SEM constraints compared to the original standards.

Table 6.1: Major OFDM parameters of 802.11p and 802.11af PHY

Parameters	802.11p	802.11af		
Bandwidth (BW)	10 MHz	6 MHz	7 MHz	8 MHz
Used subcarriers (N_C)	52	114		
Total subcarriers (N_T)	64	144	168	144
FFT points (N_{FFT})	64	128		
Subcarrier spacing (Δf)	$\frac{10MHz}{64}$	$\frac{6MHz}{144}$	$\frac{7MHz}{168}$	$\frac{8MHz}{144}$
Sampling frequency (Fs)	10 MHz	5.33 MHz	5.33 MHz	7.11 MHz
Fourier transform length	6.4 us	24 us	24 us	18 us
CP length	1.6 us	6 us	6 us	4.5 us

802.11p is defined for VC channel that tends to experience a larger delay spread than WLAN. The 802.11p symbol has 16 samples for CP (i.e. the same as in 802.11a). 802.11p guard intervals are lengthened to avoid ISI by reducing the bandwidth from 20 MHz to 10 MHz (i.e., operating at a sample frequency of 10 MHz), but this raises some challenges in the frequency domain. First, reducing bandwidth requires a higher quality factor front-end filter circuit for the higher frequency carrier compared to 802.11a. Second, in an 802.11p system, similar to 802.11a, there are 6 sub-carrier spacings used for the frequency guard per side. But reducing the sampling frequency leads to a narrowing of the frequency guard. Generally, to improve performance in VC channels with large delay spread, the timing guard is increased, narrowing the frequency guard and resulting in more strict filtering constraints. According

to empirical VC channel models in [1, 2], maximum delay spread varies depending on different propagation models and traffic environment. The RTV model for suburban street, urban canyon, and expressway, have maximum excess delay of 700, 501, and 401 ns, respectively [1]. For the V2V model, measurements in [2] show that delay spread is largest for urban areas and smallest for highway areas. The 90% measured value of delay spread for urban areas is near 600 ns which is equivalent to the duration of 6 samples in the CP. Therefore, the remaining guard interval of 1 μ s (i.e., 10 samples in the CP) is for filtering the spectral leakage to meet the SEMs specification.

On the other hand, 802.11af is defined to reuse the white spaces in the UHF band with three basic channel units (BCUs) of 6 MHz, 7 MHz, and 8 MHz. In the scope of this chapter, we take the parameters of the 6 MHz BCU to investigate the filtering method for 802.11af systems. For 802.11af channels, the delay spread is measured as less than 1 μ s [3], which is equivalent to the duration of 6 samples in the CP. Therefore, the 802.11af guard interval of 6 μ s is sufficient to avoid ISI. The remaining guard interval of 5 μ s (i.e., 26 samples in the CP) is for filtering the spectral leakage. However, the FCC rules define a strict SEM to avoid the ICI on PU channels in the UHF band. For the 6 MHz channels, the transmitted signal of TVBD devices shall maintain at least 55 dB attenuation at the edges of the channel, which is significantly larger in comparison to the original 802.11ac parent standard.

To the best of the author's knowledge, no baseband filtering solution has yet been published which has been shown suitable to meet the strict SEM criteria for either 802.11p or 802.11af. However, several methods have been shown effective at mitigating spectral leakage for the parent standards 802.11a, and 802.11ac.

The following sub-sections thus investigate state of the art methods from the 802.11a and 802.11ac research communities, and considers their application for the newer standards. Specifically, each method will be evaluated, and shown unable to meet the strict SEM criteria for 802.11p (and hence is very unlikely to satisfy the even more stringent 802.11af SEM).

The work presented in this chapter has also been discussed in:

- T. H. Pham, I. V. McLoughlin, and S. A. Fahmy, "Shaping Spectral Leakage for IEEE 802.11p Vehicular Communications," to appear in *Proceedings of IEEE Vehicular Technology Conference (VTC Spring), Seoul, Korea, May 2014* [4].

- T. H. Pham, S. A. Fahmy, and I. V. McLoughlin, “Spectrally Efficient Emission Mask Shaping for OFDM Cognitive Radios,” to be submitted to *IEEE Transactions on Communications (TCOM)*.

6.1.1 Spectral Leakage Compression

Conventionally, there are two methods that can be employed to compress the spectral leakage for OFDM-based system, namely pulse shaping and image spectrum compression. Pulse shaping, recommended in 802.11a, is effective at reducing side lobes. Considering an OFDM symbol to have IFFT length and CP length N and N_{CP} , respectively, the length of the symbol including its CP is $N_T = N + N_{CP}$, a sample $x[m]$ of the OFDM symbol ($0 \leq m \leq N_T - 1$) can be expressed in the time domain as,

$$x[m] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{i2\pi \frac{k}{N}(m-N_{CP})}, \quad (6.1)$$

where $X[k]$ denotes the frequency domain representation of the data sub-carriers. Since OFDM symbol samples are generally transmitted sequentially, this is equivalent to multiplying symbols with a rectangular window function, p . Then the transmitted OFDM samples can be expressed as;

$$x[n] = \frac{1}{N} \sum_{l=-\infty}^{\infty} \sum_{k=0}^{N-1} X[k] p[n - lN_T] e^{i2\pi \frac{k}{N}(n-N_{CP}-lN_T)} \quad (6.2)$$

In a conventional OFDM system, the window function, $p(m)$, is rectangular and simply described as;

$$p[m] = \begin{cases} 1, & m = 0, 1, \dots, N_T \\ 0, & otherwise \end{cases} \quad (6.3)$$

In pulse shaping OFDM, the window function, $p[m]$, uses a smooth rather than rectangular pulse resulting in inducing distortion in the subcarriers. One way to avoid this is to add extending parts, i.e. CP and a cyclic suffix (CS) before and after each conventional OFDM symbol respectively, and to multiply the extended symbol with a smoothing function. While the CP in conventional OFDM is used as a guard interval, here it is also used for pulse shaping. Pulse shaping extends the N_T length of the OFDM signal by a roll-off factor, β . The overhead of extending CS results in spectral loss; overlapping of the CP and CS of consecutive symbols shown in Fig. 6.1 is needed to form a transmitted symbol to reduce this loss, but causes ISI in

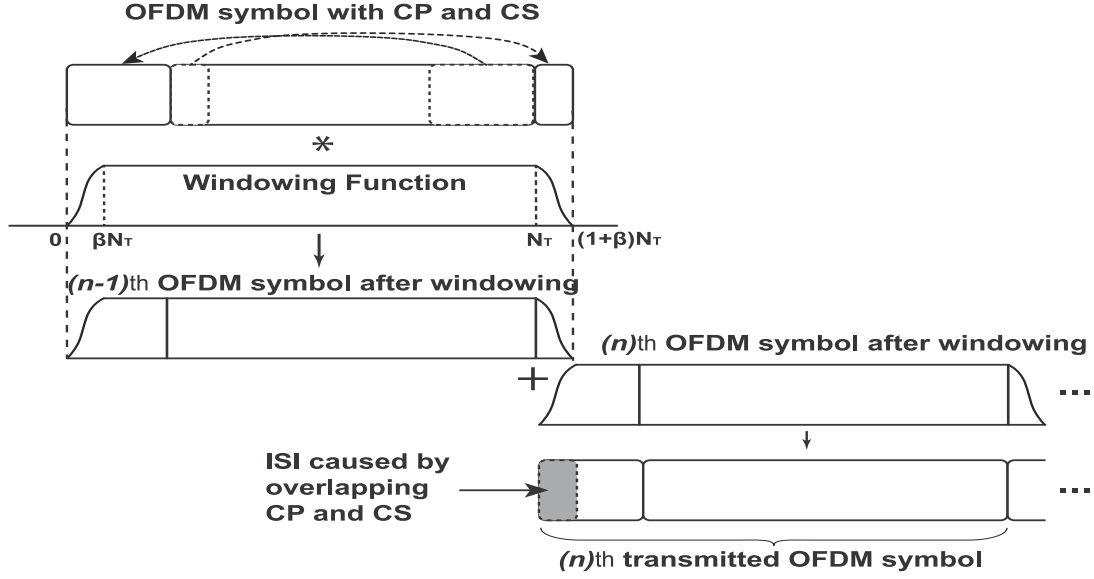


Figure 6.1: Pulse Shaping operation performed on OFDM symbols.

the overlapped region. Pulse shaping using the overlapping method is effectively equivalent to shortening the OFDM guard interval. A larger β obtains greater compression in spectral leakage but reduces the effective guard interval. When βN_T is increased to equal the CP length, the effective guard interval is reduced to zero (no guard interval) to prevent channel-induced ISI.

Image spectrum compression is implemented as an FIR filter to cancel image spectra. The Interpolation can be used at baseband to increase sampling frequency, thereby extending baseband bandwidth. Image spectra are repeats of the original baseband spectrum, present because of interpolation or digital analogue converter (DAC) effects. On one hand, the narrow band gap between main and adjacent image spectra requires a long impulse response FIR filter. On the other hand, according to the performance of FIR expressed in (6.4), the impulse response of the FIR filter h with length L_{FIR} has a similar effect to the impulse response of the overall channel in terms of inducing ISI.

$$y[n] = \sum_{i=0}^{L_{FIR}-1} h[i]x[n-i] \quad (6.4)$$

The FIR filter reduces the effective guard interval of OFDM symbols [5]. Its design also needs to deal with the tradeoff between the length of filter to avoid ISI and the transition band and attenuation of the filter to meet the requirement of SEMs.

6.1.2 Pulse shaping

Pulse shaping (using a smooth rather than rectangular pulse), recommended in 802.11a, is effective at reducing side lobes of the OFDM signal. In practical terms, pulse shaping using the overlapping method is effectively shortening the OFDM guard interval. A larger roll-off factor β means reduced spectral leakage, at the cost of reducing the effective guard interval since a number of guard interval samples are taken for pulse shaping. Three state-of-the-art smoothing functions for pulse shaping are investigated. We will present each in discrete form, before investigating their performance with different roll-off factors. The first smoothing function, denoted p_1 , is present in the IEEE 802.11a standard:

$$p_1 = \begin{cases} \sin^2(\frac{\pi}{2}(0.5 + \frac{m}{2\beta N_T})), & 0 \leq m < \beta N_T \\ 1, & \beta N_T \leq m < N_T \\ \sin^2(\frac{\pi}{2}(0.5 - \frac{m-N_T}{2\beta N_T})), & N_T \leq m < (1 + \beta)N_T \end{cases} \quad (6.5)$$

The second, proposed by Bala et al. [6], is based on a raised cosine function, denoted here as p_2 :

$$p_2 = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos(\pi(1 + \frac{m}{\beta N_T})), & 0 \leq m < \beta N_T \\ 1, & \beta N_T \leq m < N_T \\ \frac{1}{2} + \frac{1}{2}\cos(\pi(1 + \frac{m-N_T}{\beta N_T})), & N_T \leq m < (1 + \beta)N_T \end{cases} \quad (6.6)$$

The third, denoted p_3 , is based on the characteristics of functions with vestigial symmetry as derived by Castanheira and Gameiro [7]:

$$p_3 = \begin{cases} \frac{1}{2} + \frac{9}{16}\cos(\pi(1 - \frac{m}{\beta N_T})) \\ -\frac{1}{16}\cos(3\pi(1 - \frac{m}{\beta N_T})), & 0 \leq m < \beta N_T \\ 1, & \beta N_T \leq m < N_T \\ \frac{1}{2} + \frac{9}{16}\cos(\pi\frac{m-N_T}{\beta N_T}) \\ -\frac{1}{16}\cos(3\pi\frac{m-N_T}{\beta N_T}), & N_T \leq m < (1 + \beta)N_T \end{cases} \quad (6.7)$$

The compression of OFDM spectral side lobes as a consequence of pulse shaping is investigated by first assuming that the effect of the image spectrum caused by interpolation or digital-to-analogue conversion (DAC) is negligible. This assumption is noted because the band

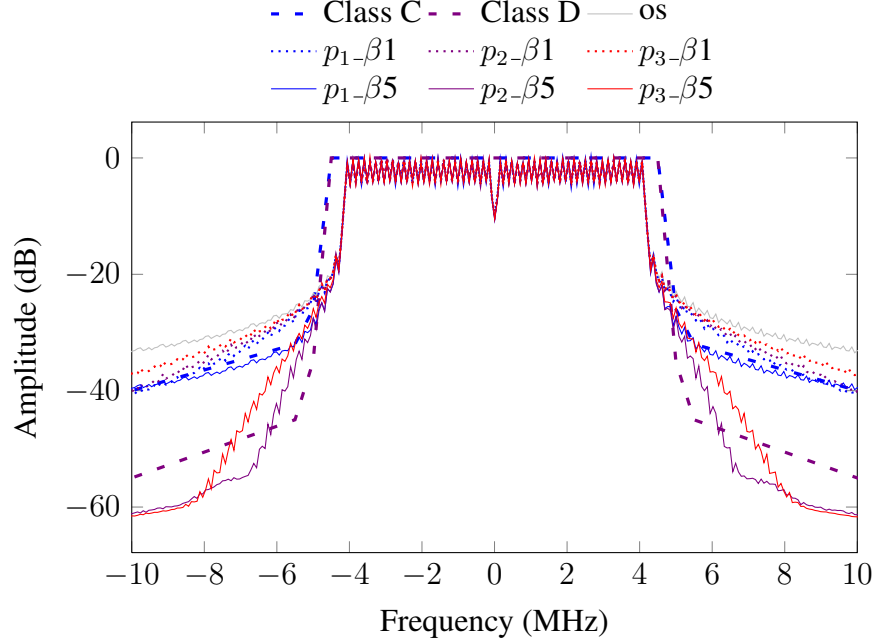


Figure 6.2: Spectral envelope due to pulse shaping OFDM symbols using three smoothing functions and different roll-off factors for 802.11p. Class C and D spectral emission mask limits are overlaid as dotted lines.

gap between the wanted spectrum and its image is relatively narrow. Thus the overlapping image spectrum can influence the effectiveness of the shaped spectral leakage. The issue will be discussed later in the section, where image cancellation is presented separately for 802.11p and 802.11af.

The three smoothing functions are simulated for otherwise identical channels and signals, and compared in Fig. 6.2. The figure reveals the spectral envelope attenuation achieved using the three smoothing functions.

In Fig. 6.2, *os* shows the original OFDM spectrum without applying pulse shaping. $p_1\text{-}\beta 1$, $p_2\text{-}\beta 1$, $p_3\text{-}\beta 1$ show the spectra of the OFDM signal using smoothing functions: $p_1(m)$ to $p_3(m)$, respectively. In each case, roll-off factors of $\beta N_T = 1$ and $\beta N_T = 5$ are shown. In the case of using one guard interval sample, the spectral leakage is reduced compared to the original OFDM signal, and $p_1(m)$ obtains better results than the other two methods, however, the shaped spectra do not meet the emission requirement of class C. When 5 CP samples are used for pulse shaping, $p_2(m)$ and $p_3(m)$ achieve a significant improvement, and in fact, $p_2\beta 5$ satisfies class C and almost meets the requirement of class D.

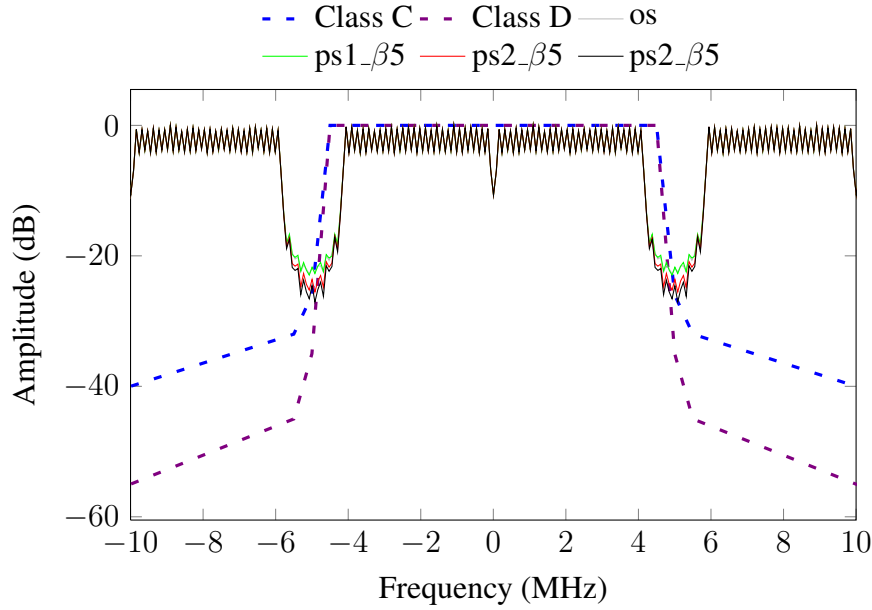


Figure 6.3: Spectrum of 802.11p OFDM symbols shaped with different winwod functions, with the presence of the image spectrum included.

Thus, we can state that, ignoring the presence of an image spectrum as noted previously, the pulse shaping method can take part of the guard interval for applying the smoothing function in order to shape the spectral leakage and nearly meet the most stringent SEM compliance.

To investigate further, Fig. 6.3 plots simulation results for pulse shaped 802.11p OFDM symbols with the presence of the image spectrum included. The image is a consequence of interpolation or DAC response. The plot shows that pulse shaping yields a response that is similar to, but slightly better than, the original OFDM signal. However, when the image spectrum is considered, pulse shaping clearly can not achieve meaningful adjacent channel signal compression. In fact, the band gap between the main spectrum and the image spectrum is insufficient for pulse shaping to achieve any significant spectral leakage decay.

In a practical system, the consequence is that almost all of the side-lobe attenuation may need to be contributed by sharp and hence both high order and accurate analogue filters. Such filters contribute design complexity, increased component count, manufacturing difficulty, and additional cost to a product.

To alleviate this, the following subsection investigates digital filtering for image spectrum cancellation, using FIR filter.

6.1.3 Image Spectrum Cancellation By FIR Filter

The critical issue for 802.11p signals to meet the stringent class D mask requirements is that the frequency guards are narrow and the frequency carrier is relatively high (5.9 GHz) compared to 802.11a. However, interpolation can be used at baseband to increase sampling frequency, and thereby extend the baseband bandwidth. Since the image spectra are repeats of the original baseband spectrum, replicated due to interpolation effects, interpolation filters can be used to cancel them.

Such filters are commonly implemented using finite impulse response (FIR) form. A cascaded integrator comb (CIC) implementation is sometimes chosen, since this can combine the interpolation and filtering steps, however while it is computationally efficient it lacks flexibility. Since the research is concerned with the tradeoff between duration of impulse response, degree of oversampling, and filter transition band sharpness, flexibility is important and thus general FIR form filters are assumed. The tradeoff mentioned above exists because the narrow band gap between main and adjacent image spectra mandates a high order filter to remove ICI, which generally implies a high order and thus long impulse response filter. Unfortunately the long impulse response of the filter has a similar effect to the impulse response of the overall channel in terms of inducing ISI. Thus the FIR filter also reduces the effective guard interval of OFDM symbols [5]. Consequently, its design contributes to the tradeoff between ISI avoidance, the transition band, and degree of filter attenuation needed to meet the SEM requirement.

Several widely used FIR implementation filters are listed in Table 6.2. These will all be investigated for image spectrum attenuation, as applied to 802.11p symbols. An empirical formula [8] is used to estimate the length of each filter in terms of attenuation A and transition band $\Delta\omega$. The specifications of the most stringent 802.11p class D SEM are used to calculate the required number of taps with L -fold interpolation, in terms of L .

It is noticeable that the required lengths of these FIR filters for 802.11p are all longer than the guard interval of the 802.11p symbol. To avoid ISI, the maximum length of the FIR filter is derived by taking into account the guard interval and the CIR. By assuming that the delay spread of the VC channel is constrained to a maximum of 600 ns (as discussed in Section 2) based on the results stated in [1, 2], the CIR is equivalent to 6 samples of the 802.11p guard interval (sampling frequency of 802.11p is 10MHz). Therefore, a remaining effective guard interval of 10 samples is available for filtering. However, when the filter is used in a

Table 6.2: Popular window-based FIR filter lengths

Window	Stopband Attenuation	Filter Length, N	Length for 802.11p
Hamming, HM	-26.5dB	$\frac{6.22\pi}{\Delta\omega}$	$N \approx 31L$
Hanning, HN	-31.5dB	$\frac{6.65\pi}{\Delta\omega}$	$N \approx 33L$
Blackman, BM	-42.7dB	$\frac{11.1\pi}{\Delta\omega}$	$N \approx 55L$
Kaiser, KS	—	$\frac{A-7.95}{2.23\Delta\omega}, A > 21$ $\frac{5.78}{\Delta\omega}, A < 21$	$N \approx 33L$
Chebyshev, CW	—	$\frac{2.06A-16.5}{2.29\Delta\omega}$	$N \approx 67L$

transmitter, a matched filter is required at the receiver [5] with equivalent length, meaning that the remaining guard interval is effectively halved: only 5 samples remain for transmitter filtering.

Given that L -fold interpolation is used at the transmitter, the permitted FIR filter length becomes $5 \times L$, constituting one of the rules for the FIR filter design process.

To visualise this, a simulation is performed with $L = 8$, to evaluate filtered spectra using

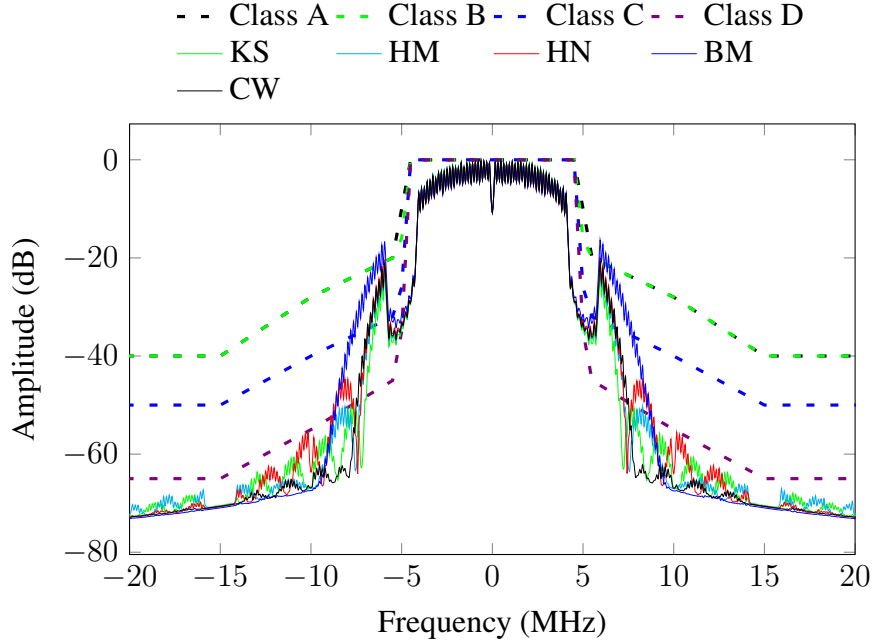


Figure 6.4: Spectra of OFDM symbols for 802.11p using different FIR interpolation filters, with $L = 8$.

each window, for 802.11p symbols. The spectral responses are plotted in Fig. 6.4, where the same OFDM signal as in Fig. 6.3 has been filtered by the FIR interpolation filters, and compared to the SEMs. In the figure, the filtered spectra obtained by using Kaiser, Hamming, Hanning, Blackman, Chebyshev windows are compared (denoted using the abbreviations in Table 6.2). In each case, two prominent auxiliary peaks, visible beside the main spectrum, are the biggest impediments to satisfying the SEM criteria. In detail, the Blackman filtered spectrum slightly exceeds the class A limits, whereas the remaining filters are able to meet the requirements of classes A and B but not of classes C and D. In fact, none of the filters are even close to class C and D compliance. Hence, given the effective guard interval of 802.11p, FIR filtering clearly does not provide a solution.

The simulation results show that the common filtering methods used at interpolated base-band are even not close to meet the strict SEM requirements of 802.11p. Although not shown here, this is of course equally true of the more stringent 802.11af SEM.

This result implies that 802.11p and 802.11af implementations must rely on sharp front end RF and analogue filtering, which typically results in an increased total system cost and reduced power efficiency.

6.2 A Spectrum Efficient Shaping Method

The discussions above have revealed that the main challenge to conforming with strict SEMs is the narrow frequency guard which must accommodate a very sharp filter transition between pass and stop bands, since the stop-band attenuation is high. In this section, we briefly explain the method before building upon its foundation to derive a CR architecture for OFDM spectral leakage mitigation which we will then evaluate for both 802.11p and 802.11af.

6.2.1 New Spectral Leakage Filtering Method

In a conventional approach, pulse shaping is only employed with small roll-off factors. This is because large roll-off factors involve longer filters, reducing the effective guard interval. Given the narrow frequency guard of the OFDM spectrum for the new standards, and the amount left after accounting for the effects of CIR and matching filters, pulse shaping under such constraints is unable to cancel the image spectrum: in fact, even if the entire guard interval was to

be used, this may be insufficient for the very stringent class D SEM in 802.11p, and the SEM of 802.11af. Thus our new method takes a different approach. Instead of using a large proportion of the guard interval for FIR filtering, we allow the pulse shaping to occupy a significant portion of the guard space, with large roll-off factors. To obtain the significant spectral leakage reduction necessary, the frequency guard needs to be increased. It thus involves introducing a frequency guard extension technique. Then, given a wider frequency guard, pulse shaping with large roll-off factors can achieve significant side lobe compression of the OFDM signal, and the required transition band for FIR filtering is extended, which means a shorter FIR filter is able to attenuate the image spectrum.

The method thus involves three steps:

- The IFFT length is multiplied by a factor M , and the sampling frequency similarly increased by a factor M , to maintain the same subcarrier spacing. Given this, the allocation vector is formed to add data symbols at lower sub-carriers that are the same as those in the original IFFT, while the remaining sub-carriers are zero-padded.
- Next, pulse shaping is applied in the normal way, to meet the given SEM constraint.
- Finally, L' -fold interpolation is used to allow simple filtering to remove the image spectrum.

Based on the proposed approach, we build a flexible CR architecture which is demonstrated to achieve the SEM requirements for both 802.11p (all classes A, B, C and D) as well as 802.11af in the UHF band.

6.2.2 Novel CR Filtering Architecture

A CR architecture for OFDM implies the agility to handle non-contiguous (NC) transmission of symbols (NC-OFDM) as well as the ability to adapt to different frequency bands, bandwidths and timing synchronisation regimes. For the purposes of this chapter, a CR architecture is developed which combines transmission of NC-OFDM symbols with switched sampling frequency, supporting both 802.11p and 802.11af. In particular, the architecture adaptively extends the frequency guard as required, and performs both pulse shaping and FIR interpolation filtering to meet the most strict SEM requirements of both standards. It should be understood

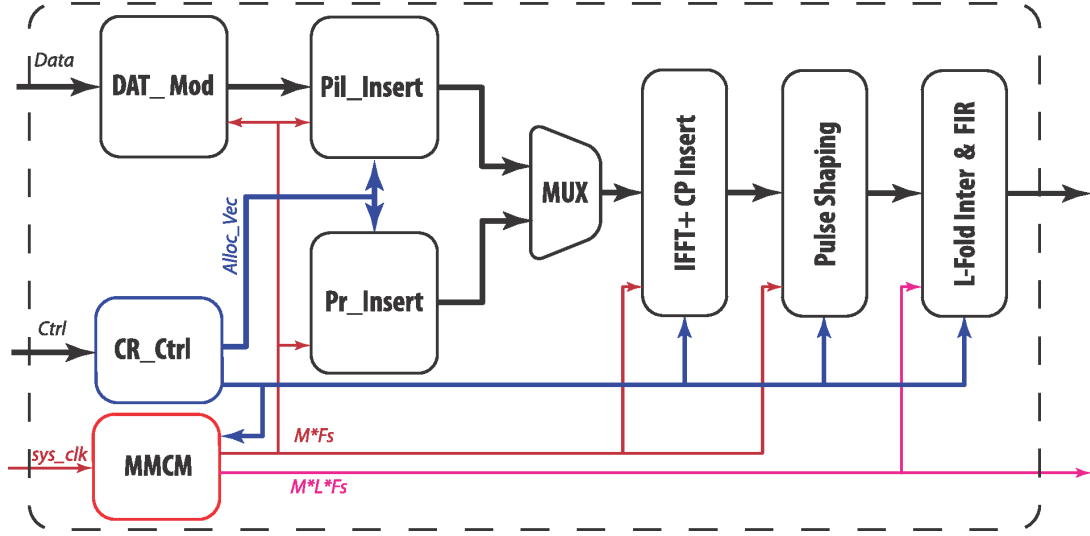


Figure 6.5: The CR-Based architecture for adaptive OFDM spectral leakage shaping.

that this CR architecture is designed to demonstrate compliance with the more difficult standards: it could trivially be de-rated to the much less stringent 802.11a and 802.11ac parent standards.

The proposed CR-based transmitter architecture structure is presented in Fig. 6.5, as implemented on a Xilinx FPGA for experimental purposes. As can be seen, the architecture consists of the baseband sub-modules, including *Pil_Insert* which flexibly inserts data symbols and pilots from the data modulator, *DAT_Mod*, into an OFDM symbol according to the current allocation vector (*Alloc_Vec*). *Pre_Insert* inserts the preamble symbol while *IFFT+CP Insert* is an IP core that with flexibly reconfigurable IFFT length and CP insertion. *PulseShaping* performs pulse shaping with a smoothing function for which the roll-off factor can be changed from small, for relaxed spectral shaping, to large, for more stringent spectral shaping. *L-Fold Inter&FIR* performs L' -fold interpolation, with L' being controllable on a symbol-by-symbol basis. After interpolation, the FIR block is used to filter out the image spectrum. In addition, for the CR architecture, the cognitive control sub-module (*CR_Ctrl*) is used to modify sub-module parameters to match SEM requirements imposed from the higher layers (i.e. it adjusts timing, bandwidth, frequency band and SEM requirements). The mixed-mode clock manager (*MMCM*) is another integrated IP core used to manage the sampling clock (F_s), which is set according to the filter performance requirements and operating frequency band.

In addition, the *MMCM* allows the transmitter to reduce the degree of filtering (i.e. degree of spectral leakage shaping) when transmission power is reduced: since transmit power reduction naturally reduces ICI. This is particularly important for lower power operating modes in which a lower sampling frequency, less filtering complexity, and reduced transmission amplitude all contribute to power savings.

Compare this with the 802.11p prototype presented in [9], which was adopted for direct device-to-device communication between smartphones. That innovative prototype was able to adaptively increase transmission power to extend communication range. However, the system was based on an 802.11a hardware solution and baseband, and did not investigate the increased spectral leakage when the transmitted signal was amplified to increase range (at which point it would not be likely to meet the 802.11p SEM requirement).

By contrast, the method proposed and implemented in this chapter, is able to apply a more stringent SEM filter when transmission power is increased such that ICI exceeds a given threshold. In particular, *CR_Ctrl* is invoked to change the IFFT length to M times the original IFFT, while *Alloc_Vec* extends the frequency guard and *MMCM* increases F_s according to the required IFFT length. Moreover, *CR_Ctrl* changes *PulseShaping* to use a large roll-off factor, reduces the L -fold interpolation (since $L' \times M$ is constant) and shortens the FIR length to meet the more stringent SEMs. On the other hand, when a device and access point are in closer proximity, the transmission power can be reduced such that the spectral leakage is small, and thus filtering can be relaxed. In this case, *CR_Ctrl* is invoked to change the IFFT length back to the original, and employ *PulseShaping* with a small roll-off factor. Moreover, *L-Fold Inter&FIR* switches back to a normal range in order to reduce the amount of computation. It should be noted that the additional computation needed for signal processing in the baseband (which uses low cost, low power components), can be more than compensated for by relaxing the specification of the RF front-end design since the analogue filtering requirements are so much less strict.

The following Section presents the application of the proposed CR architecture in performing stringent filtering to achieve the SEM specifications of both 802.11p and 802.11af respectively.

6.3 Simulation Results and Discussion

6.3.1 Application for 802.11p

Continuing the assumption from Section 6.1 that the CIR length does not exceed 600 ns. Therefore, the effective guard interval which is equivalent to the length of 10 samples of the original CP, i.e., $10 \times 100 = 1000$ ns is used for the pulse shaping and FIR filter. By choosing an DAC sampling frequency of 80 MHz, the sampling frequency of 802.11p is increased by 8 times ($L \times M = 8$) compared to the original (10 MHz). Two options denoted as *Prop1*, *Prop2* are studied for 802.11p. *Prop1* doubles the size of IFFT, i.e., $M = 2$, this means doubling the sampling frequency, to extend the frequency guard. Then 4-fold interpolation, i.e., $L = 4$, is required to obtain a sampling frequency of 80 MHz. *Prop2* quadruples the size of IFFT, i.e., $M = 4$; Then 2-fold interpolation, i.e., $L = 2$, is performed. Based on the results in subsection 6.1.2, $p_2(m)$ is employed with $\beta N_T = 5 \times M$, that is equivalent to the length of 5 samples of the original CP, i.e., 500 ns. It should be noted that after extending the frequency guard, the number of samples in the symbol including CP, is increased M times. Fig. 6.6 shows the shaped spectrum of the method after interpolation in the baseband, at 80 MHz. The result is also compared to the original spectrum denoted *Conv*, and the specifications of classes C and D. The main spectrum of *Prop1*, *Prop2* almost satisfy class D. The image spectrum of *Prop1* is present at ± 40 MHz and ± 20 MHz whilst *Prop2* has an image spectrum at ± 40 MHz.

A simple short length FIR filter is needed to cancel the image spectra. The remaining guard interval for the transmitter filter and matched filter is 500 ns. Therefore, the maximum impulse response of the FIR filter is 250 ns, which is equivalent to $2.5 \times M \times L$ samples at the 80 MHz sampling frequency.

FIR filters are designed for *Prop1*, *Prop2* using a Kaiser window. Because the frequency guard of *Prop1* is still relatively narrow, it requires an FIR filter with the length of 20 samples to cancel the image spectrum. Fig. 6.7 shows the result of spectrum filtering for *Prop1* in comparison to the original OFDM spectrum and class C, D SEMs. As can be seen in the *Prop1* spectrum, there are still two small peaks caused by the image spectrum. These peaks are compressed by the FIR filter to meet the class D requirement. Slight distortion is present in the main spectrum because of the effect of the FIR filter. *Prop2* has a wider frequency guard compared to *Prop1*. The FIR filter only requires a length of 12 samples to cancel the

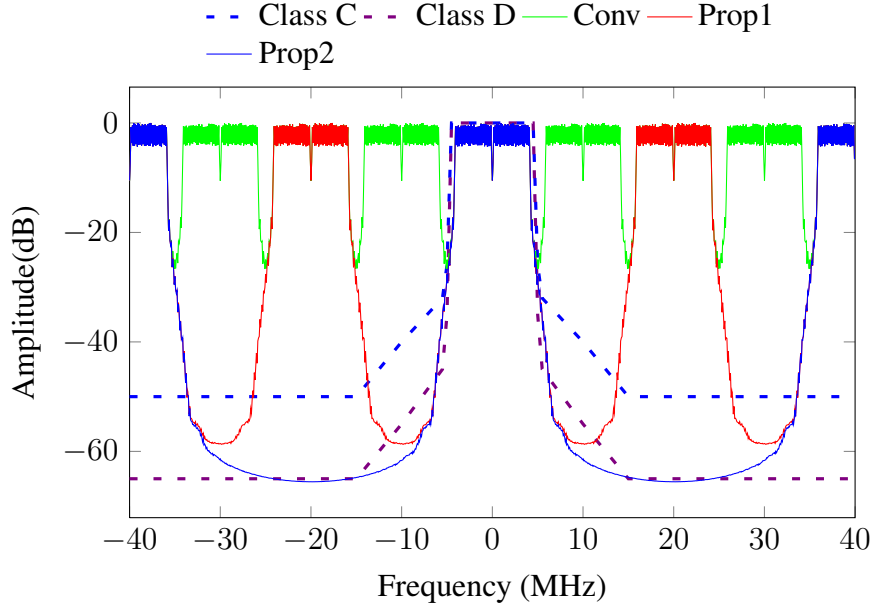


Figure 6.6: Spectrum of 802.11p signal of the method after interpolation.

image spectrum and the remaining effective guard interval of 200 ns is reserved. Fig. 6.8 shows the result of spectral filtering for *Prop2* and *Prop1* with respect to the class C and D SEMs. The image spectrum of *Prop2* can be cancelled by a short length FIR filter whilst the image spectrum of *Prop1* still remains larger in magnitude. Hence, *Prop2* meets the class D specification.

The simulation results demonstrate that the proposed technique for shaping spectral leakage can meet the specification of class D, the most stringent of the four 802.11p SEMs. *Prop2* obtains better performance in terms of distortion and effective guard interval compared to *Prop1*, but pays the cost of a higher computational requirement due to the increased IFFT size.

6.3.2 Application for 802.11af

To shape the spectral leakage for 802.11af, the assumption from Section 6.1, that the CIR length does not exceed 1 μ s (equivalent to 6 samples in the CP), is maintained. Therefore, the effective guard interval, which is equivalent to the length of 26 samples of the original CP, is used for the pulse shaping and FIR filter. By choosing a DAC sampling frequency of 48 MHz, the output sampling frequency of 802.11af is increased by 8 times ($L \times M = 8$) compared to the original (6 MHz). The simulation results of shaping the spectral leakage for 802.11af are presented with

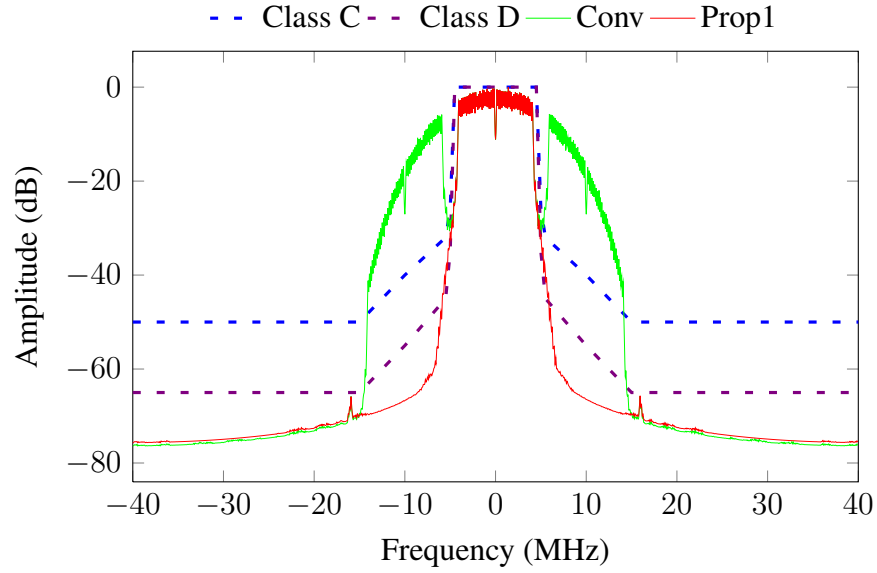


Figure 6.7: Filtered Spectrum of 802.11p signal using option *Prop1*.

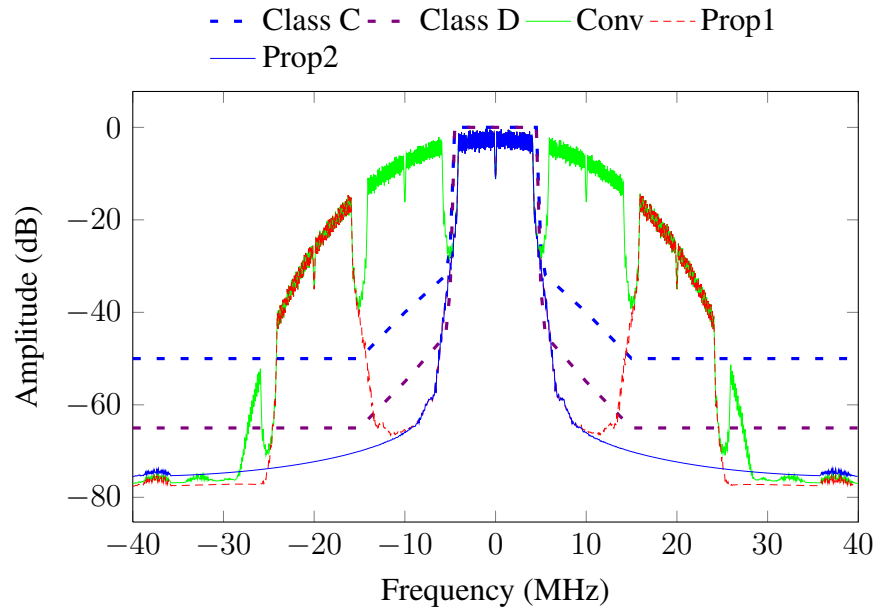


Figure 6.8: Filtered Spectrum of 802.11p signal using option *Prop2*.

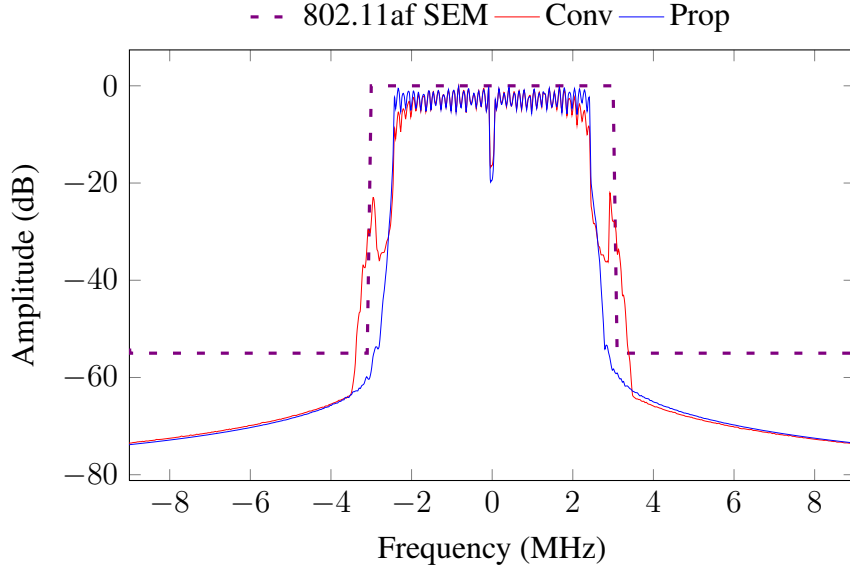


Figure 6.9: Filtered Spectrum of 802.11af signal.

a comparison between the proposed method and the conventional approach which makes use of the state of the art pulse shaping and FIR filter. In the conventional approach, pulse shaping uses 2 samples in the CP for a smoothing function and the length of FIR filter cancelling the image spectrum is allowed to be $96 \left(\frac{26-2}{2} \times 8 \right)$ to avoid ISI. The FIR filter is designed using a Kaiser window. The proposed method quadruples the size of the IFFT, i.e., $M = 4$, in order to extend the frequency guard. Pulse shaping is configured to employ $p_2(m)$ with $\beta N_T = 20 \times M$, that is equivalent to the length of 20 samples of the original CP. Then 2-fold interpolation, i.e., $L = 2$, is required to obtain a sampling frequency of 48 MHz. The allowed FIR filter length is equivalent to 3 samples of the original CP to cancel the image spectrum while still not causing ISI. Fig. 6.9 illustrates the results of shaping spectral leakage for 802.11af.

Because of the limited length, the band transition of the FIR filter is not narrow enough. This results in the spectrum of the conventional method, *Conv* having two side peaks and causes a distortion in the main spectrum. Therefore, the conventional method still has a big gap to meet the SEM requirement of 802.11af. To fit the filtered spectrum of the conventional method to the 802.11af SEM, one way that may be considered is to deactivate the high index sub-carriers (i.e. to use null-subcarriers). This can effectively extend the frequency guard, but results in an obvious loss of spectral efficiency. On the other hand, the spectrum of the method not only meet the SEM specifications but also presents a reserved gap that can potentially be

used to pack in sub-carriers in order to enhance the spectral efficiency.

In order to investigate the spectral efficiency enhancement available through the proposed method, the number of occupied sub-carriers is modified in a simulation to fit the spectrum of the conventional and proposed methods to the 802.11af SEM specification. In the conventional method, the attenuation of the FIR filter needs to be smaller, about -35 dBc, to compress the image spectrum at the edge of the bandwidth (3 MHz), that is around -20 dBc, to -55 dBc. With the limited length of the FIR filter, as mentioned above, the transition band is calculated theoretically based on the Kaiser window formula in Table 6.2. The transition band is required to be 0.83 MHz, equivalent to 21 subcarrier spacings, resulting in the guard band of 42 subcarrier spacings for both sides of 802.11af signal spectrum. This means that the number of occupied sub-carriers in the conventional method should be smaller than 102 to reserve enough frequency guard for FIR filtering. However, the simulation in Fig. 6.10 shows that the filtered spectrum of the conventional method ($94_{subcarConv}$), which employs 94 sub-carriers, is almost able to meet the SEM requirement. On the other hand, the spectrum of the proposed method has a reserved frequency gap that allows more sub-carriers can be used. The filtered spectrum of the method ($124_{subcarProp}$), employing 124 sub-carriers, illustrated in Fig. 6.10, still fits inside the 802.11af SEM. The results shows that the proposed method is not only able to meet the requirements of 802.11af but also can potentially enhance the spectral efficiency significantly. In fact, the method increases the spectral efficiency by 32% compared to the conventional method.

6.4 Summary

In this chapter, shaping the OFDM leakage spectrum has been investigated at baseband within a CR architecture, in order to meet stringent spectral emission mask (SEM) requirements. In particular, this research considers two relatively new standards, 802.11p and 802.11af, which are defined for the physical layer and largely based upon existing standards. In both cases, the extended physical layers are scaled to encourage reuse of existing hardware, devices and designs, but the resulting systems are then subject to much more stringent SEMs. The research relies upon a combination of interpolation, IFFT length adjustment, pulse shaping and FIR image suppression filtering, to mitigate against spectral leakage into adjacent channels.

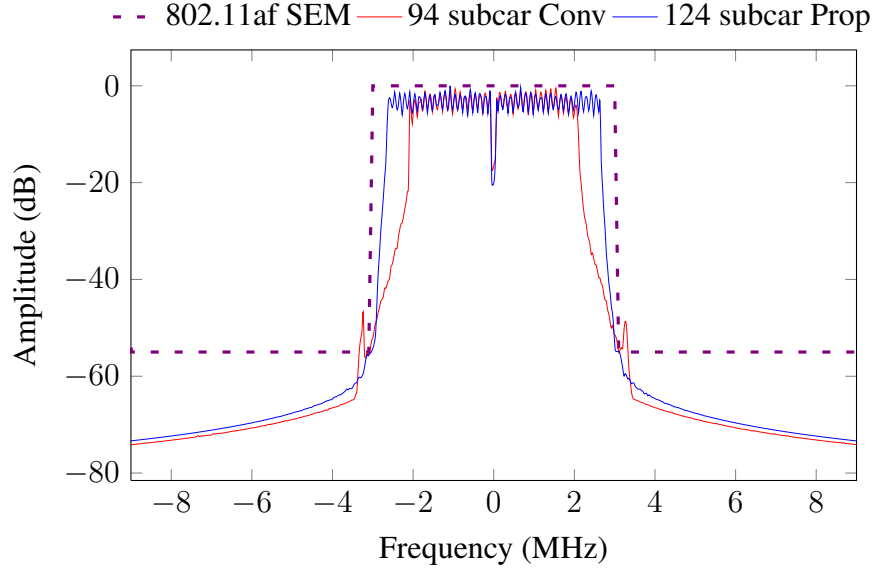


Figure 6.10: Fitting Filtered Spectrum of 802.11af signal to SEMs.

Simulations show that the proposed architecture can meet the specification of the four 802.11p classes A to D, as well as the stringent FCC-imposed SEM for 802.11af in the UHF band. The proposed method is also shown able to improve the achievable spectral efficiency for reuse of Television White Spaces in the 802.11af standard by 32%, given equivalent transmission power, compared to conventional approaches which need to drop the outermost subcarriers in order to meet SEM requirements. In addition, the architecture has the ability to adaptively change the degree of spectral leakage filtering in response to transmission power. The computation of filtering can be reduced when transmission power is low, but when transmission power is high, it is able to extend to meet the strict SEM specification of both 802.11p and 802.11af. Furthermore, the architecture is capable of adjusting clock rate, bandwidth, and frequency band on a symbol-by-symbol basis, in order to implement an agile CR solution.

Chapter 7

A Novel Architecture for Multiple Standard Cognitive Radios

Chapter 8

Conclusion and Future Work

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